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LITERATURE SURVEY AND PRELIMINARY EVALUATION OF STREAMBANK PROTECTION METHODS

by

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

A preliminary study of streambank erosion control was conducted with the major emphasis on an extensive literature survey of known streambank protection methods. In conjunction with the survey, preliminary investigations were conducted to identify the mechanisms that contribute to streambank erosion and to evaluate the effectiveness of the most widely used streambank protection methods. The results of the literature survey and the two preliminary investigations are presented herein.

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20. ABSTRACT (Continued) Appendices include: (1)

The text of the "Streambank Erosion Control Evaluation and Demonstration Act of 1974" ~~is~~ presented in Appendix A. (2) A list of commercial concerns that market streambank protection products ~~is~~ provided in Appendix B. (3) Appendix C contains a glossary of streambank protection terminology. (4) A detailed bibliography resulting from the literature survey ~~is~~ provided in Appendix D, and (5) a listing of selected bibliographies related to streambank protection are provided in Appendix E.

THE CONTENTS OF THIS REPORT ARE NOT TO BE USED FOR ADVERTISING, PUBLICATION, OR PROMOTIONAL PURPOSES. CITATION OF TRADE NAMES DOES NOT CONSTITUTE AN OFFICIAL ENDORSEMENT OR APPROVAL OF THE USE OF SUCH COMMERCIAL PRODUCTS.

PREFACE

The study reported herein was performed from July 1974 to 15 October 1976 by the U. S. Army Engineer Waterways Experiment Station (WES) for the Office, Chief of Engineers, under Work Unit 02, "Literature Survey and Evaluation of Bank Protection Methods," authorized by Section 32 of the Water Resources Development Act of 1974, Public Law 93-251. Section 32 may be cited as the "Streambank Erosion Control Evaluation and Demonstration Act of 1974."

This study was a multilaboratory effort. It was planned by Mr. N. R. Oswalt, Chief, Spillways and Channels Branch, under the general supervision of Messrs. J. L. Grace, Chief, Structures Division, and H. B. Simmons, Chief, Hydraulics Laboratory. The streambank erosion study and the identification of new methods for streambank protection were the responsibility of Dr. E. B. Perry of the Soil Mechanics Division (SMD) Research Group under the direct supervision of Mr. C. L. McAnear, Chief, SMD, and the general supervision of Mr. J. P. Sale, Chief, Soils and Pavements Laboratory. The literature search and preliminary investigation of the effectiveness of various streambank protection methods were performed by Messrs. M. P. Keown and E. A. Dardeau, Jr., of the Environmental Simulation Branch (ESB) under direct supervision of Mr. J. K. Stoll, Chief, ESB, and under the general supervision of Messrs. B. O. Benn, Chief, Environmental Systems Division, and W. G. Shockley, Chief, Mobility and Environmental Systems Laboratory (MESL). Acknowledgment is made to Mr. J. G. Kennedy, Data Handling Branch, MESL, who contributed significantly to this effort. This report was prepared by Messrs. Keown, Oswalt, Perry, and Dardeau.

COL G. H. Hilt, CE, and COL J. L. Cannon, CE, were the Directors of WES during the study and preparation of the report. Mr. F. R. Brown was Technical Director.

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CONVERSION FACTORS, U. S. CUSTOMARY TO METRIC (SI) AND METRIC (SI) TO U. S. CUSTOMARY UNITS OF MEASUREMENT

Units of measurement used in this report can be converted as follows:

Multiply	By	To Obtain
U. S. Customary to Metric (SI)		
inches	2.54	centimetres
feet	0.3048	metres
miles (U. S. statute)	1.609344	kilometres
square feet	0.09290304	square metres
square yards	0.8361274	square metres
acres	4046.856	square metres
cubic yards	0.7645549	cubic metres
cubic feet per second	0.02831685	cubic metres per second
feet per second	0.3048	metres per second
tons (short)	907.1847	kilograms
pounds (force) per square foot	47.88026	pascals
degrees (angular)	0.01745329	radians
Fahrenheit degrees	0.555	Celsius degrees or Kelvins*
Metric (SI) to U. S. Customary		
millimetres	0.03937007	inches
metres	3.280839	feet
centimetres per second	0.3937007	inches per second
metres per second	3.280839	feet per second
tons (metric) per cubic metre	0.8427	tons (short) per cubic yard

* To obtain Celsius (C) readings from Fahrenheit (F) readings, use the following formula: C = 0.555(F - 32). To obtain Kelvin (K) readings, use: K = 0.55(F + 459.67).

LITERATURE SURVEY AND PRELIMINARY EVALUATION OF STREAMBANK PROTECTION METHODS

PART I: INTRODUCTION

1. In a letter dated 14 June 1974,* subject, "Streambank Erosion Control Evaluation and Demonstration Act of 1974," the Office, Chief of Engineers (OCE), directed the U. S. Army Engineer Waterways Experiment Station (WES) to conduct a preliminary study of streambank erosion control. The major emphasis of the study was to be an extensive literature survey of known streambank protection methods. In conjunction with the survey, preliminary investigations were to be conducted to identify the mechanisms that contribute to streambank erosion and to evaluate the effectiveness of the most widely used streambank protection methods. The results of the literature survey and the two preliminary investigations are contained in this report.

2. Personnel of three technical laboratories at the WES (Hydraulics, Soils and Pavements, and Mobility and Environmental Systems) initiated this work on 15 July 1974. An interim evaluation report on streambank protection was submitted to OCE on 24 September 1974. A table summarizing the causes of erosion and typical bank protection methods as a function of maximum flow rate was included in that report and is included herein for general information (Table 1). After the interim report was submitted, work continued until the literature search was completed on 15 October 1976.

PART II: LITERATURE SURVEY

3. A comprehensive search for literature sources relevant to streambank protection methods was initiated by the WES in August 1974 in response to the requirements of the Streambank Erosion Control Evaluation and Demonstration Act of 1974 (Appendix A). A list of appropriate key words was compiled and used to search the libraries of the following agencies for relevant literature sources:

- a. Technical Information Center, WES, Vicksburg, MS.
- b. Hydraulic Engineering Information Analysis Center, WES, Vicksburg, MS.
- c. Mississippi River Commission, Vicksburg, MS.
- d. U. S. Army Engineer District, Kansas City, MO.
- e. Office, Chief of Engineers, Washington, D. C.
- f. U. S. Geological Survey, Reston, VA.
- g. The Engineer School, Fort Belvoir, VA.
- h. Coastal Engineering Research Center, Fort Belvoir, VA.
- i. Water Resources Institute, Washington, D. C.
- j. Department of Transportation, Washington, D. C.
- k. Library of Congress, Washington, D. C.
- l. American Forestry Association, Washington, D. C.
- m. Environmental Law Institute, Washington, D. C.
- n. National Geographic Society, Washington, D. C.
- o. Transportation Research Board, Washington, D. C.

4. In addition to the agencies listed in paragraph 3, the following selected government agencies, universities, commercial concerns, and research organizations were contacted to locate relevant literature that had not had widespread circulation, as well as to inquire about the effectiveness and costs of currently used streambank protection methods:

- a. U. S. Army Engineer Divisions, Lower Mississippi Valley, Vicksburg, MS, and Ohio River, Cincinnati, OH.
- b. U. S. Army Engineer Districts, Rock Island, IL; Vicksburg, MS; Kansas City, MO; San Francisco and Sacramento, CA; Baltimore, MD; Pittsburgh, PA; Louisville, KY; and Nashville, TN.

c. U. S. Department of Agriculture, Agricultural Research Service, Oxford, MS; Forest Service, Washington, D. C.; and Region 5, San Francisco, CA.

d. U. S. Department of Transportation, Federal Highway Administration, Washington, D. C., and Sevierville, TN.

e. U. S. Department of the Interior, National Park Service, Denver, CO; and Bureau of Reclamation, Denver, CO.

f. Louisiana Highway Department, Baton Rouge, LA.

g. Texas Highway Department, Austin, TX.

h. University of California, Water Resources Center, Berkeley, CA.

i. Colorado State University, Engineering Research Center, Fort Collins, CO.

j. University of Iowa, Institute of Hydraulic Research, Iowa City, IA

k. Central Hydraulics Laboratory of France, Maisons-Alfort, France

l. Advance Construction Specialties Company, Memphis, TN.

m. Air Logistics Corp., Pasadena, CA.

n. American Excelsior Co., Sheboygan, WI.

o. ARMCO Steel Corporation, Washington, D. C.

p. Bekaert Gabions, Reno, NV.

q. Boiardi Products Corp., New York, NY.

r. Bomanite Corp., Palo Alto, CA.

s. Bowie Industries, Bowie, TX.

t. Carthage Mills, Inc., Cincinnati, OH.

u. Celanese Fibers Marketing Co., New York, NY.

v. Conwed Corp., Minneapolis, MN.

w. Construction Techniques, Inc., Cleveland, OH.

x. DuPont, Wilmington, DE.

y. Edward E. Gillen Co., Milwaukee, WI.

z. ERCO Systems, Inc., New Orleans, LA.

aa. Erosion Control, Inc., West Palm Beach, FL.

bb. Finn Equipment Co., Cincinnati, OH.

cc. GAF Corp., New York, NY.

dd. Grass Growers, Inc., Plainfield, NJ.

ee. Grass Pavers, Ltd., Royal Oak, MI.

ff. Grifflon Company, Inc., Houston, TX.

gg. Gulf States Paper Corp., Tuscaloosa, AL.

hh. Hold-That-River, Inc., Houston, TX.

ii. Hudson Pulp and Paper Corp., Palatka, FL.

jj. Kaiser Aluminum, Oakland, CA.

kk. Koch Brothers, Inc., Kansas City, KS.

ll. Louisiana Industries, Bossier City, LA.

mm. Ludlow Textiles, Dalton, GA.

nn. Maccaferri Gabions, Inc., Williamsport, MD.

oo. Menardi-Southern, Houston, TX.

pp. Monsanto Textiles Co., St. Louis, MO.

qq. Owens-Corning Fiberglass Corp., Toledo, OH.

rr. Phillips Petroleum Co., Bartlesville, OK.

ss. Reinco, Plainfield, NJ.

tt. Spidel Foundations Harbor and Marine Corp., Benton Harbor, MI.

uu. Superior Fiber Mulch, Hunt Valley, MD.

vv. United States Textures Sales Corp., Baton Rouge, LA.

ww. VSL Corp., Los Gatos, CA.

xx. Asphalt Institute, College Park, MD.

yy. Bituminous Coal Research, Inc., Monroeville, PA.

zz. Portland Cement Association, Skokie, IL.

A tabulation of the commercial organizations that market streambank protection products (with their respective addresses and products) is provided in Appendix B. Also in Appendix B are the addresses of the research organizations that direct part of their efforts toward the study of streambank protection.

5. Literature sources were also located by interrogating available computer data banks. Computer bibliographies relevant to streambank protection were obtained from the following information systems (system names in parentheses):

a. North Carolina State University, Water Resources Research Institute, Raleigh, NC (SWRSIC)

b. Smithsonian Institution, Smithsonian Scientific Information Exchange, Washington, D. C. (SSIE)

c. U. S. Department of Agriculture, Washington, D. C. (CRIS)

d. U. S. Department of Agriculture, National Agricultural Library, Beltsville, MD. (CAIN)

e. U. S. Department of Commerce, National Technical Information Service, Springfield, VA. (NTISearch)

f. U. S. Department of Defense, Defense Supply Agency, Defense Documentation Center, Alexandria, VA. (DOD On-Line Retrieval System)

g. U. S. Government Legislative Branch, Library of Congress, Washington, D. C. (SCORPIO)

h. University of Arizona, School of Renewable Natural Resources, Tucson, AZ. (WAMIS)

i. University of Wisconsin, Water Resources Information Center, Madison, WI. (WRSIC)

6. For the purposes of the literature search, streambank protection methods were broken down into five groups:

a. Group A - Placement of single-component revetment

b. Group B - Placement of mattresses, matting, and pavement

c. Group C - Construction of bulkheads

d. Group D - Stabilization of soil

e. Group E - Construction of river training structures

Group A includes single components, such as blocks, riprap, sacks, etc., that are used to cover a streambank and are generally not connected with each other or stabilized by wire, grout, cable, or other devices. Group B includes materials, such as articulated concrete mattresses and pavements, that are unitized and reinforced to increase stability and longevity and are used primarily for protecting large bank surfaces on major river systems. The materials in Groups A and B require support from the bank to remain in place, but bulkheads (Group C) support themselves (sometimes also supporting the bank) and generally serve to physically separate the soil-water interface. Several materials or methods are commonly used to improve the resistivity of soil to stream erosion; these are included in Group D. The methods in Group E do not protect the streambank directly, but deflect stream currents away from erodible banks. Thirty-eight materials, structures, and techniques (loosely termed "methods" herein) for protecting streambanks were identified during this study. These were categorized into one of the five groups discussed above and are presented in Table 2. Appendix C is a glossary of terms, including those in Table 2.

7. As potentially useful literature sources were located, each was examined for content and, if accepted, placed in an alphabetical listing under one or more of the streambank protection categories listed in Table 2. The resulting bibliography is presented as Appendix D. Also, a selected listing of bibliographies related to streambank protection was assembled and is presented in Appendix E.

PART III: PRELIMINARY INVESTIGATION OF STREAMBANK EROSION

Types of Streambank Erosion

8. There are several types of streambank erosion* that are described by the American Society of Civil Engineers Task Committee on Channel Stabilization Works and others.[1-7] These types are:

- a. Attack at the toe of the underwater slope, leading to bank failure and erosion. The greatest period of bank failure normally occurs in a falling river at the medium stage or lower.[8]
- b. Erosion of soil along the bank caused by current action.
- c. Sloughing of saturated cohesive banks, i.e. banks incapable of free drainage, due to rapid drawdown.
- d. Flow slides (liquefaction) in saturated silty and sandy soil.
- e. Erosion of the soil by seepage out of the bank at relatively low channel velocities.[9-11]
- f. Erosion of upper bank, river bottom, or both, due to wave action caused by wind or passing boats.[12-15]

Mechanics of Streambank Erosion

9. The mechanics of streambank erosion are related to the geometry and hydraulic characteristics of the stream.[16] Figure 1 shows that the highest water velocities and deepest parts of the channel are at the points of bend where the thalweg lies closest to the concave bank.[17] During periods of extreme floods, the highest water velocities lie closest to the convex bank, as shown in Figure 2.[17] Figure 3 shows that the maximum water velocity occurs just below the water surface.[17] The effect of vegetation on the variation of velocity with depth below the water surface is shown in Figure 4.[18,19] A manual for establishing protective stands of perennial vegetation on soils of low productivity has been published by the U. S. Environmental Protection Agency.[20]

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* Natural or man-induced bank recession, channel deepening, or both.

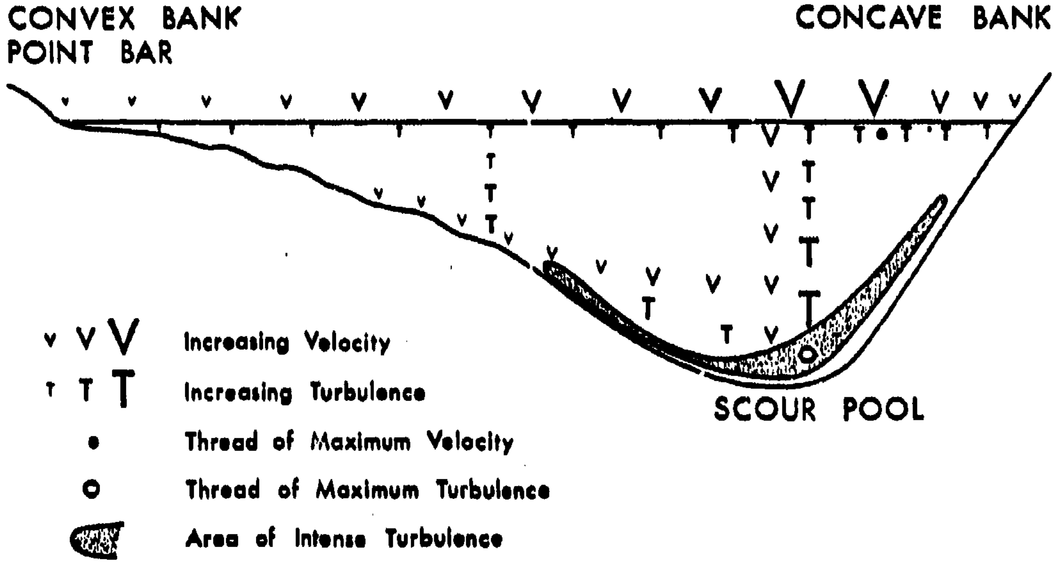


Figure 1. Velocity and turbulence in a river bend (Reference 17)

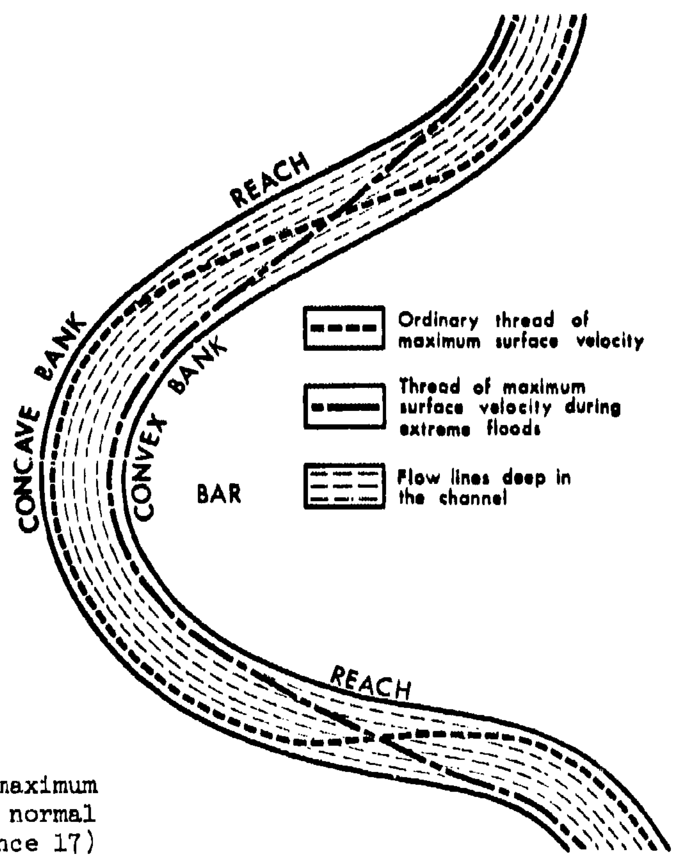


Figure 2. Location of maximum surface velocity during normal and flood flows (Reference 17)

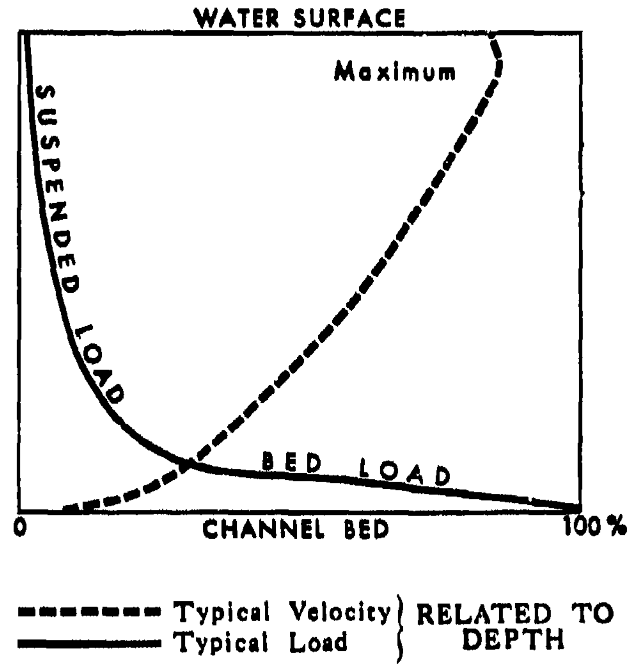


Figure 3. Variation of velocity and sediment load with depth below water surface (Reference 17)

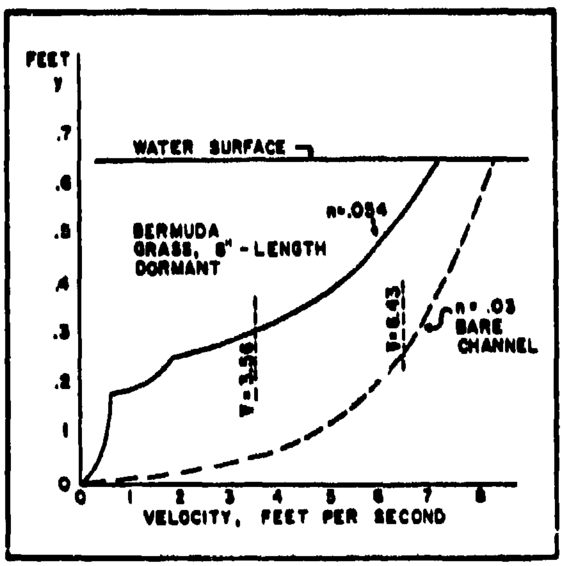


Figure 4. Influence of vegetation on variation of velocity with depth below water surface (adapted from Reference 19)

Fisk[21] described bank recession as follows (Figure 5):

> Scouring in the thalweg destroys the equilibrium between the saturated substratum sand and the mass of river water. If the bank consists of sandy material, sloughing occurs immediately. If the bank consists of clay, sloughing may occur only after considerable scour has taken place.

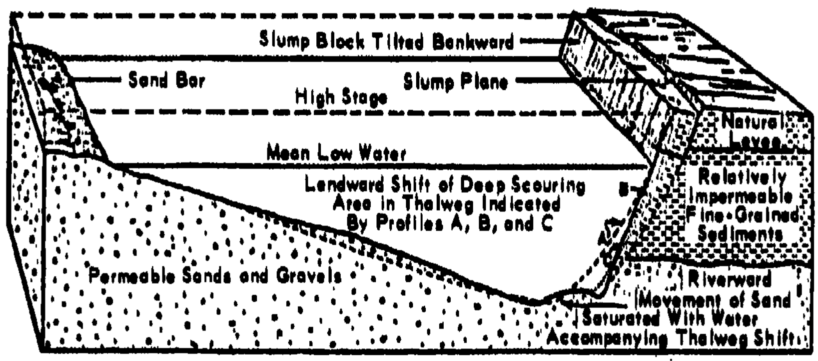


Figure 5. Bank recession through slumping (Reference 21)

10. Until the use of revetments in modern times, clay plugs (channel fill deposits of highly plastic clays formed by filling of oxbow lakes produced by cutoffs of meander loops) were the major restrictive influence on river activity and have been instrumental in determining the history of the Mississippi River.[22] According to Kesel et al.,[23] bank stability is decreased by rapid fluctuations of the river level, mainly at high-water periods; these high-water periods or rapid fluctuations cause increased pore-water pressure and thus increase the weight and decrease the effective shear strength of the bank material. It has been estimated that the lower bank protection represents about 75 percent of the area to be protected and about 90 percent of the total cost of protection.[24]

11. Krinitzsky and others[25-27] have postulated the influences of the geology of riverbank soils on the mechanics of streambank erosion along the lower Mississippi River. Data for the studies were taken from revetted sites for which periodic hydrographic surveys and soil property data obtained in connection with foundation investigations were available. The revetments are believed to cause the thalweg to deepen to a

greater extent than it would if the banks were not revetted. However, since there are few bends along the lower Mississippi River that are not revetted, the processes evaluated were considered applicable to present conditions.

12. Figure 6 shows the alluvial fill in the vicinity of a

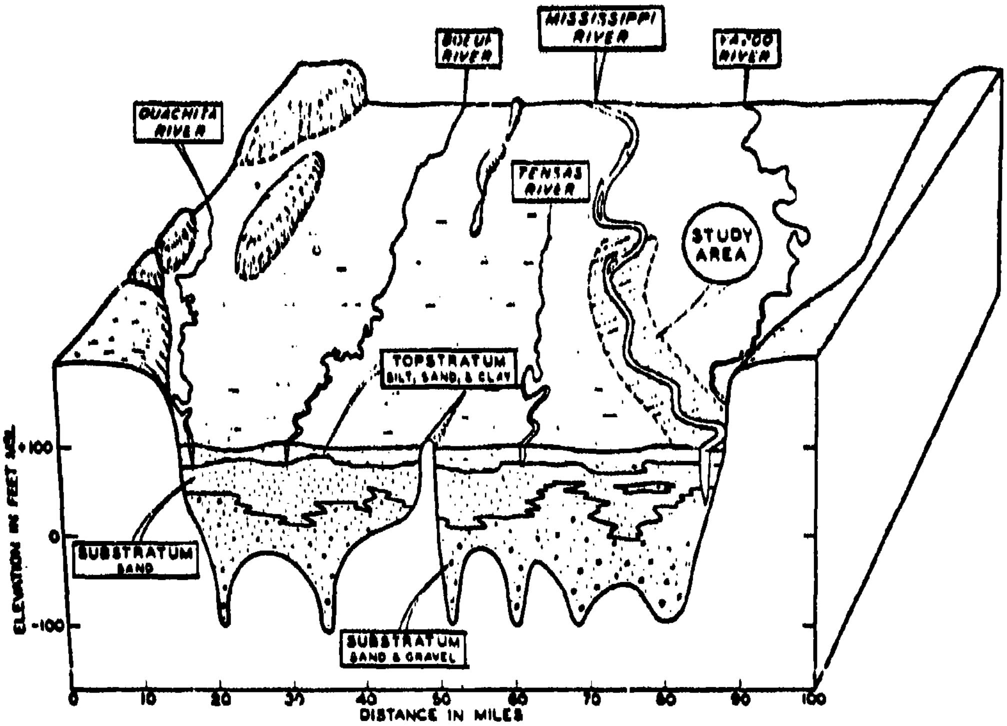


Figure 6. Alluvial fill in vicinity of a study area (Reference 25)

study area. Erosion of soil in the scour pool was found to steepen the riverbank slope near its toe, which precipitated a limited shear or flow failure. Such failure might be limited to subaqueous failure, or it might trigger other failures in the bank, resulting in an upper bank failure. A direct relation was found between the magnitude of seasonal scour in the thalweg pool and the sizes of the subaqueous bank failures. The type of soil in the bank had an important modifying influence on subaqueous bank failure, and shear failure in the upper bank occurred when the shearing stresses in the bank material exceeded the available shear strength of the soil.

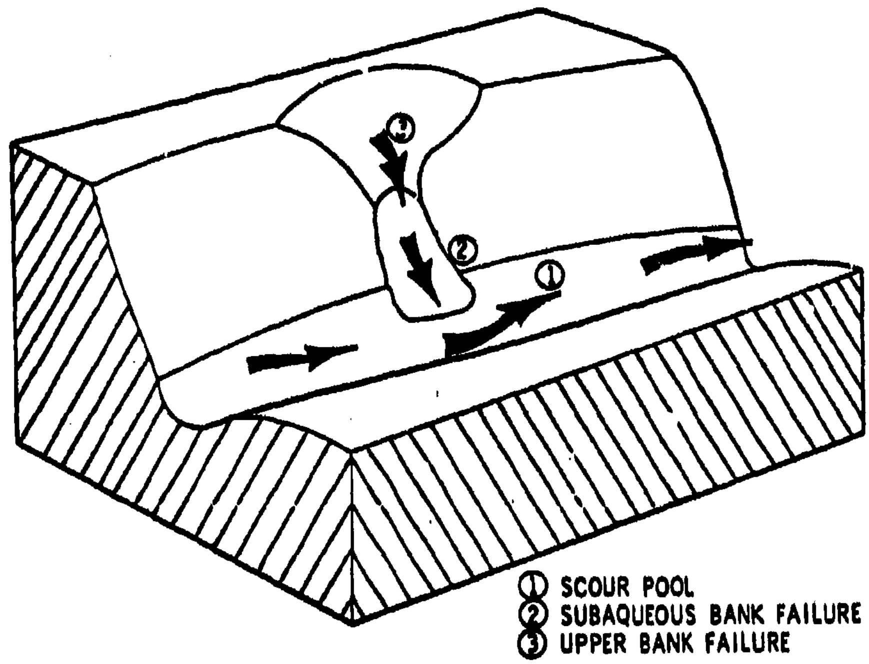
13. Flow failures were initiated in layers of saturated, low-relative-density sands in the substratum portion of the riverbank. These sand layers liquefy when strain or vibration produces excess pore pressures that reduce the effective stress and, consequently, the shear strength to zero. Flow failures are recognized by the bowl-shaped indentations that occur in the bank or by the comparatively narrow neck through which the sediment is discharged. During flood periods, flow slides frequently occur on the convex bank near the point at which the thread of maximum surface velocity impinges upon the riverbank (Figure 2). Empirical criteria have been developed at the WES to assess the susceptibility of riverbanks to flow failure.[25,28]

14. Figure 7a shows the general process of bank erosion in the alluvial valley of the lower Mississippi River.[25] Bank failures in the deltaic clays (Figure 7b) were found to result from the deepening of the thalweg pool and the accompanying oversteepening of the underwater slopes of the river bendways, thereby leading to a shear bank failure, which usually involved the full height of the bank.[26,27] The influence of geology of riverbank soils on the mechanics of bank failure in the alluvial valley of the lower Mississippi River is shown in Figure 8.[25]

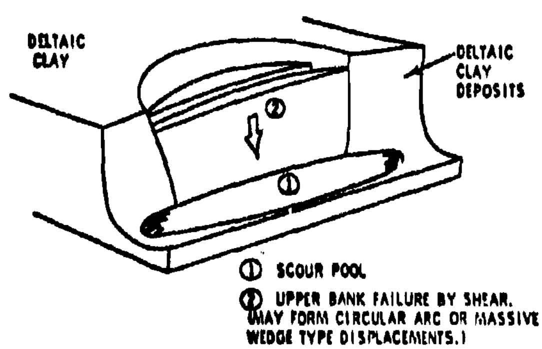
Physical Characteristics of Stable Channels

15. Seepage investigations in the Mississippi and Arkansas River Valleys have resulted in a correlation between field permeability and grain size, as shown in Figure 9.[29] The bottom velocities for initiation of bed-load movement as a function of grain size are shown in Figure 10.[30]

16. Field observations and laboratory studies have shown that the depths of cross sections increase with the resistances of riverbanks to erosion.[4,31] The failure to recognize the need for a large width-depth ratio in sands has been recognized as a mistake, since channel widths increase until stability is achieved.[32] Schumn[33-35] conducted an



a. Alluvial valley



b. Deltic clays

Figure 7. General process of bank erosion in the lower Mississippi River (References 25 and 27)

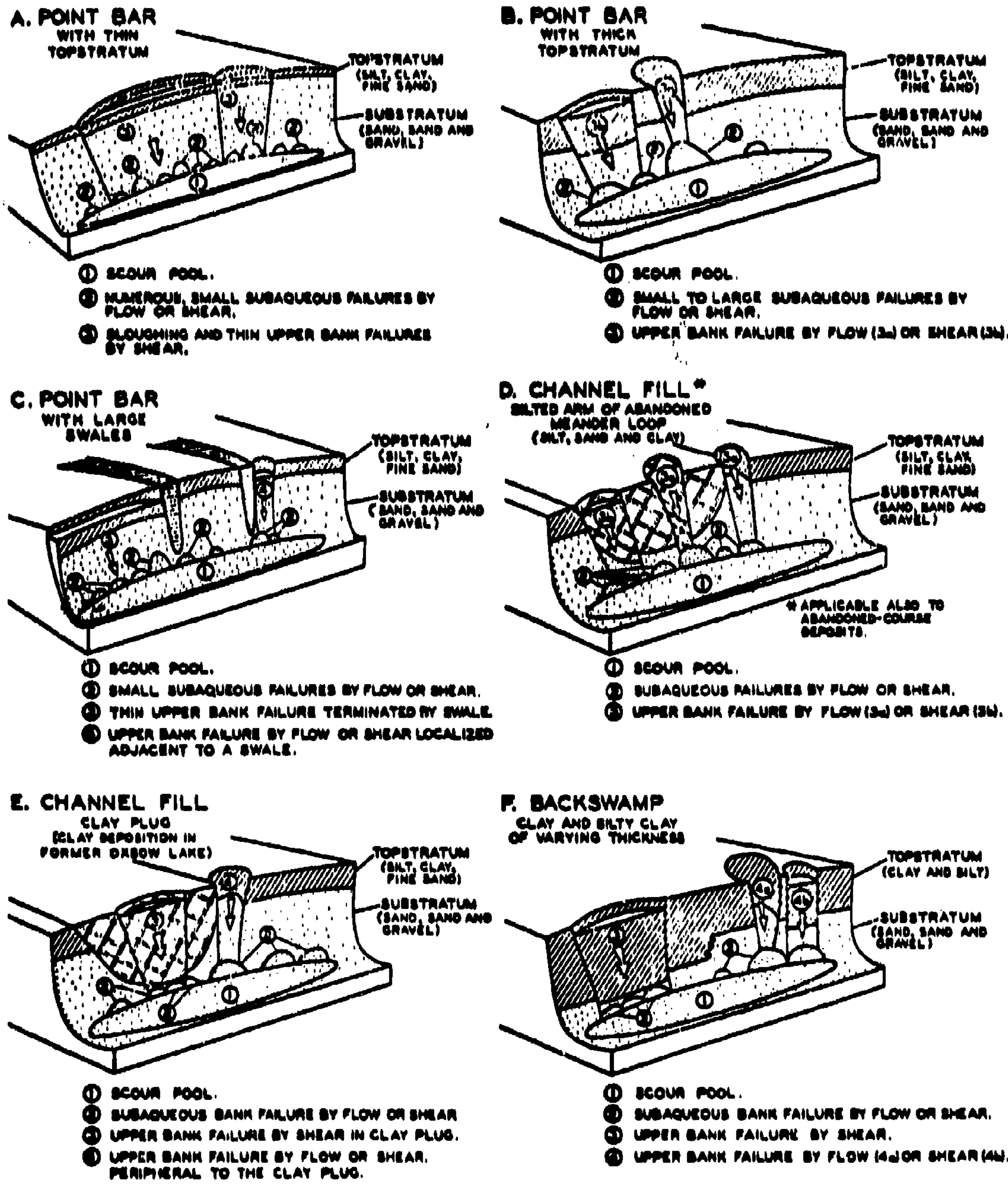
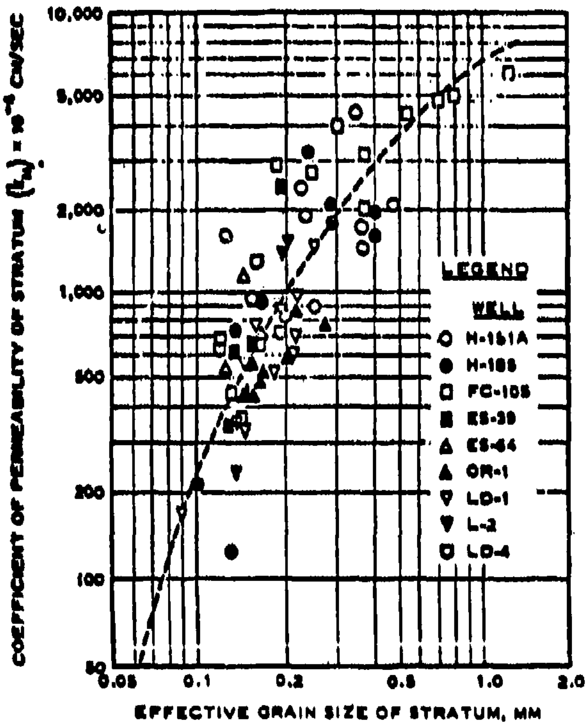


Figure 8. Influence of geology of riverbank soils on the mechanics of bank failure in the alluvial valley of the lower Mississippi River (Reference 25)



NOTES: k_H BASED ON FIELD PUMPING TESTS.
D_{10} IS THE SIZE IN MM OF THE MAXIMUM PARTICLES IN THE MINUS 10 PERCENT FRACTION (FRACTION FINER THAN 90 PERCENT OF THE SAMPLE BY WEIGHT).

Figure 9. Field permeability versus grain size in the Mississippi and Arkansas River Valleys (Reference 29)

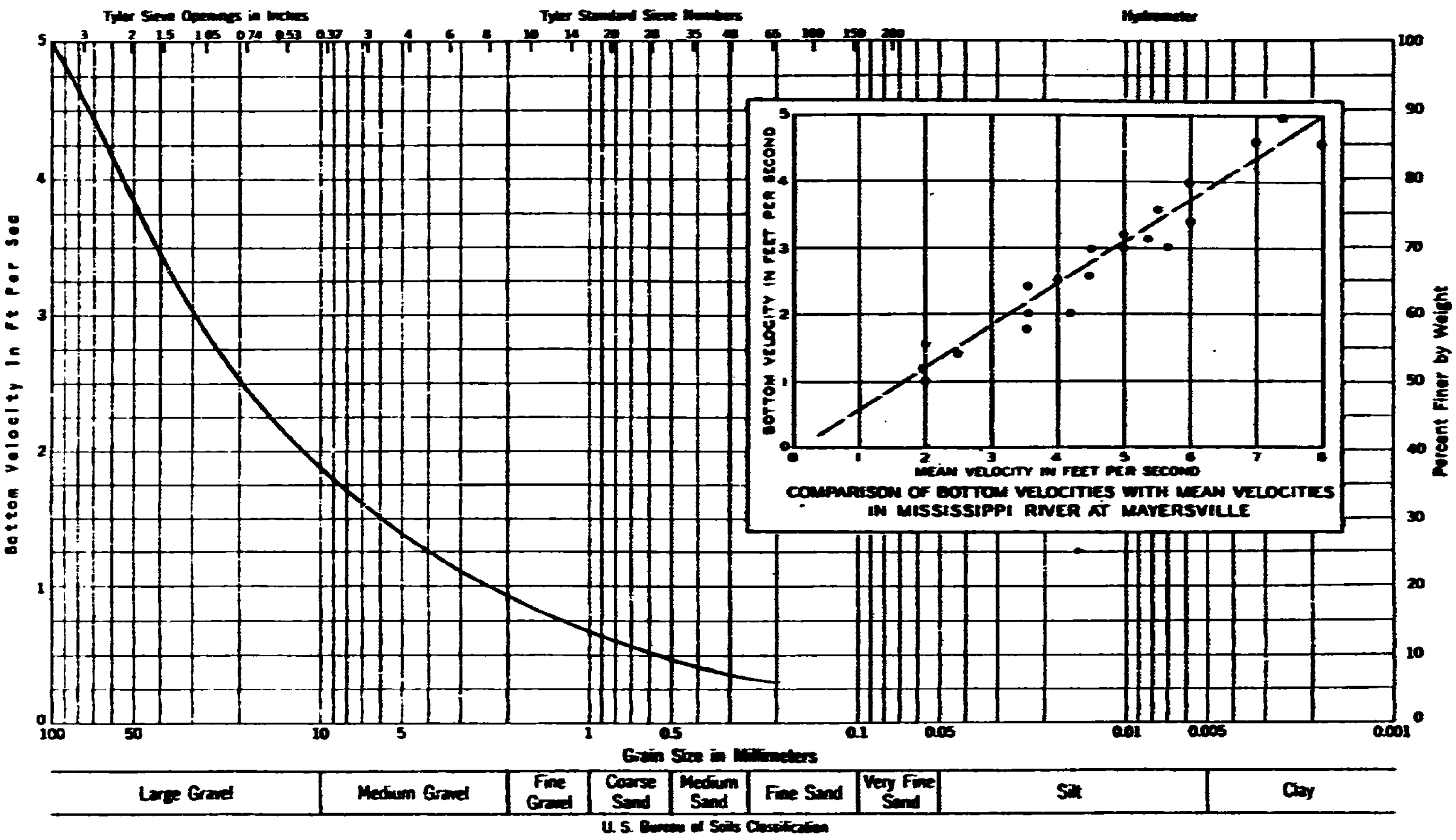


Figure 10. Bottom velocities for initiation of bed-load movement versus grain size (Reference 30)

investigation of ephemeral streams (i.e. streams in which flow is directly related to storm runoff and is not continuous for periods greater than 24 hr) that transported only small (less than 20 percent) quantities of coarse gravel. In this investigation Schumn developed a relation (Figure 11) for width-depth ratio versus percent silt-clay (material smaller than 0.074 mm*) in the banks and channel as a criterion for

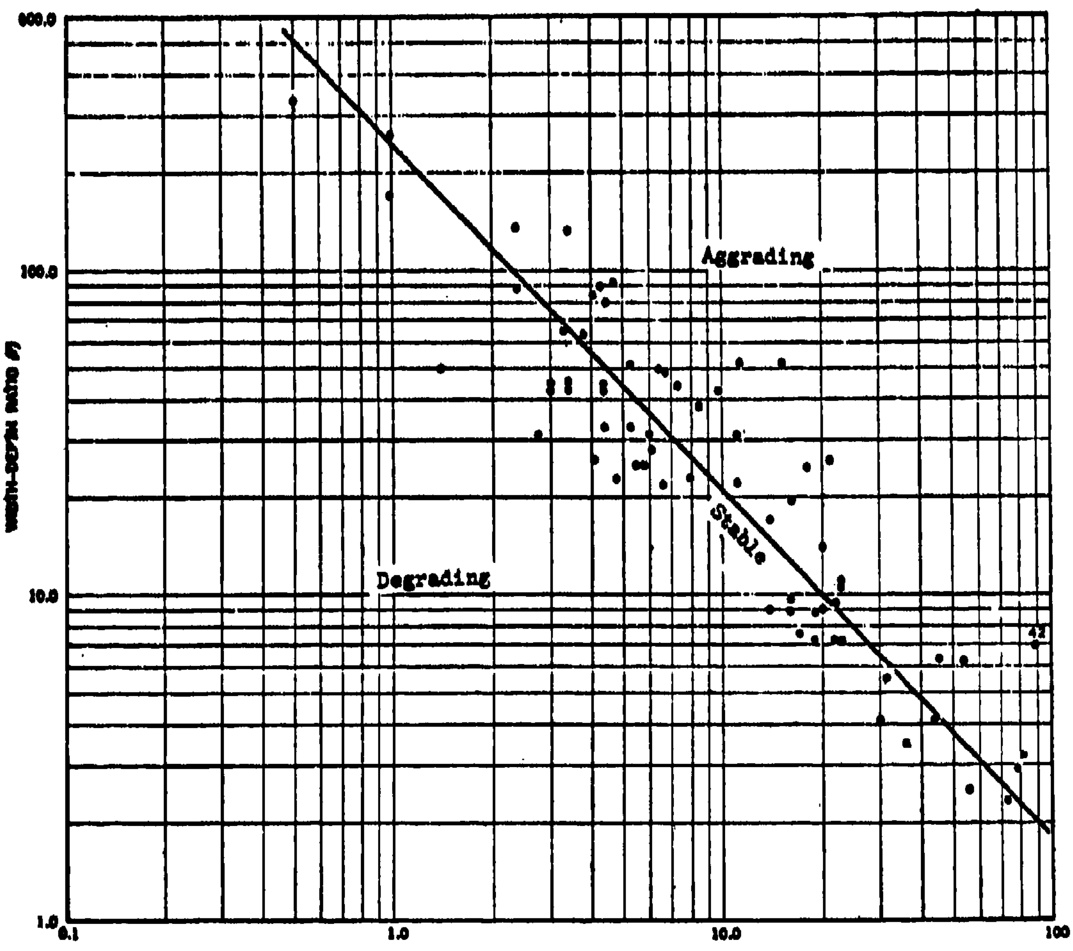


Figure 11. Width-depth ratio versus percent silt-clay in banks and channels as a stability criterion for ephemeral streams (Reference 33)

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* A table of factors for converting metric (SI) units of measurement to U. S. customary units and U. S. customary to metric (SI) is presented on page 5.

degrading or aggrading.[33] Stream gradient shows an inverse relation to percent silt-clay in banks and channels (Figure 12).[34] He classified

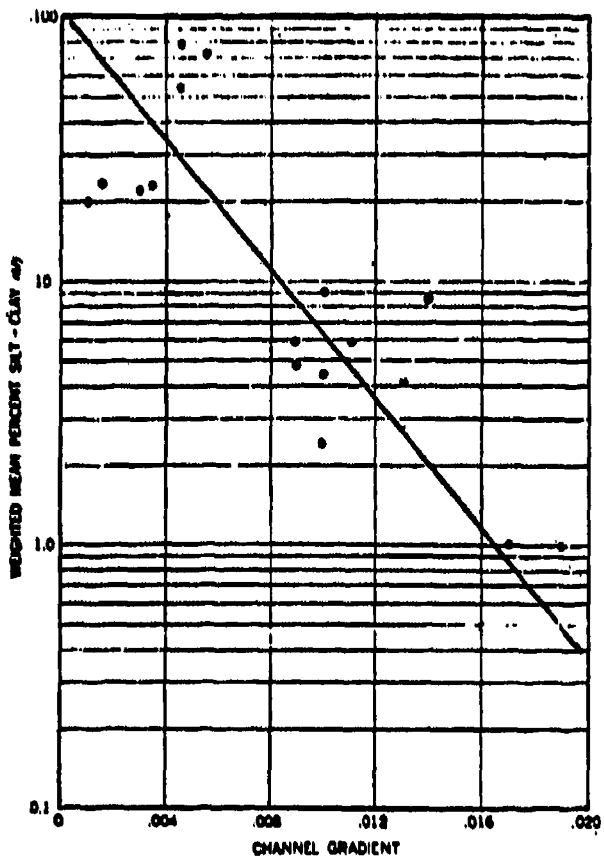


Figure 12. Relation between percent silt-clay in banks and channels and channel gradient for stable ephemeral streams (Reference 34)

alluvial river channels transporting less than 20 percent coarse gravel as stable, eroding, or depositing based on channel stability and the predominant mode of sediment transport as shown in Table 3.[35]

17. If a large amount of fine sediment is present in the flow, it may deposit on the banks and in the channel and thereby decrease the erodibility of the material. Conversely, fine sediment may increase both the viscosity and specific weight of the fluid and the tractive force (force per unit area exerted by the flow of the river past the

banks and channel), thus enhancing the instability of the channel.[36]

18. Brice[37] developed a relation between bank erodibility as a function of sinuosity index (ratio of channel length to length of meander-belt axis) and channel width for the Calamus River in Nebraska (Figure 13). Differences in bank erodibility were mainly determined by vegetal growth along the banks.

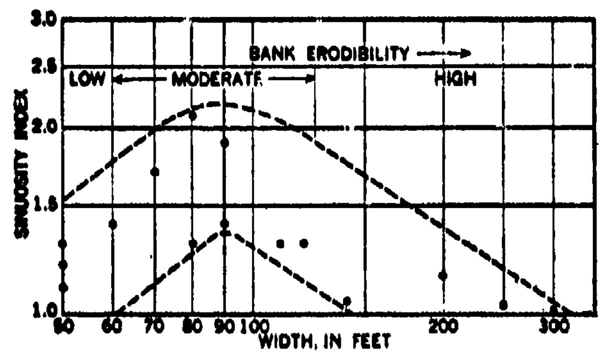


Figure 13. Bank erodibility as a function of sinuosity index and channel width for the Calamus River, Nebraska (Reference 37)

19. Wall[38] conducted a study to determine the influence of soil gradation on channel stability in the Savannah River. In studies of both trouble-free and troublesome areas, no correlation was found between channel stability and soil gradation.

20. Goss[39] conducted a study of nine unstable and six stable reaches of the Washita River in Oklahoma to determine the relation between physical and mineralogical properties and streambank erodibility. The clay mineralogy and bulk density were very similar for all samples. The sand grains from the stable areas were less rounded than those from the unstable areas and were usually coated with clay or organic matter. The sand grains from the unstable areas were relatively clean. DeCoursey and Hunt[40,41] conducted a study of stable test reaches from 75 streams in and adjacent to Oklahoma. The bank and bed material properties were related to the channel characteristics through a statistical analysis and using regime and tractive force theories of channel design.

21. Flaxman[42] conducted an investigation along 12 channels in six

western states to determine channel stability in cohesive soils. Field measurements were made in channels relatively free of vegetation to determine the tractive power, which is the product of the channel slope, hydraulic radius, specific weight of water, and average velocity. The observed distinction between eroding and stable channels was recognized as being a subjective determination, with only qualitative results possible. Undisturbed samples of nearly saturated cohesive soils were taken from the test channels to determine unconfined compressive strengths. Figure 14 shows the relation developed between channel stability as a function of tractive power and unconfined compressive strength.[42]

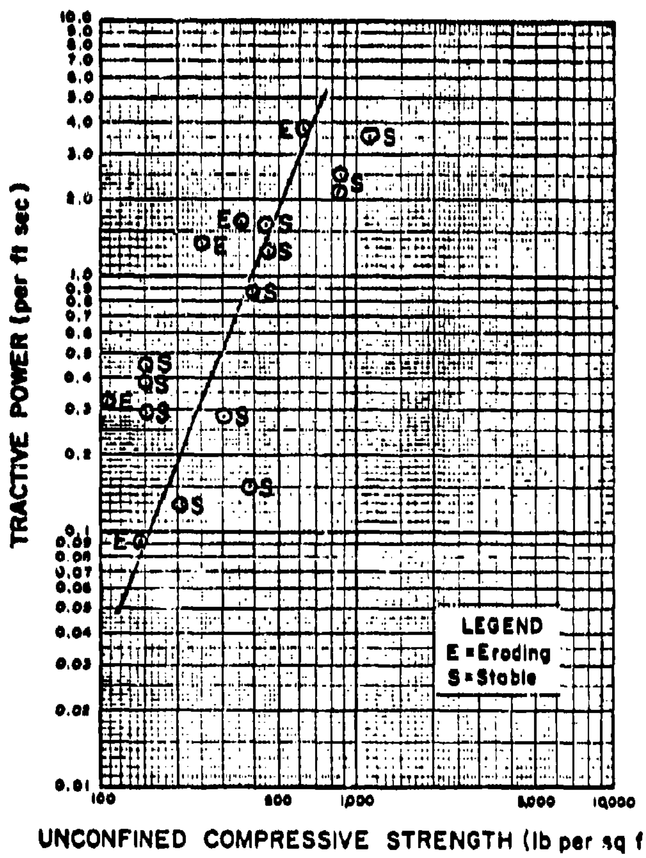


Figure 14. Channel stability as a function of tractive power and unconfined compressive strength (Reference 42)

Methods of Studying Streambank Stability

22. Historically, methods used to study channel stabilization problems have been as follows:[29,43-45]

   a. Using movable-bed hydraulic models.

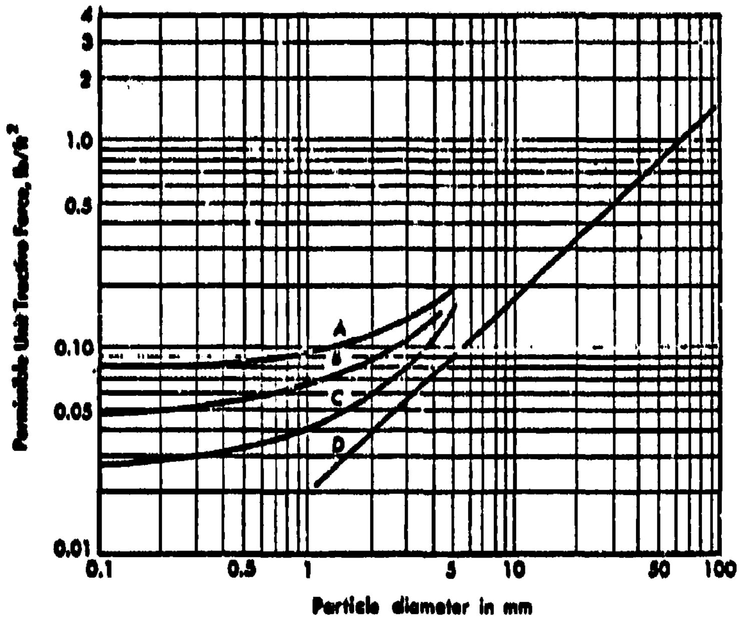
   b. Constructing regulating works in the river in increments, using the river itself as a model.

Although movable-bed models with erodible banks have been used to reproduce sections of banks where active caving is present in the prototype stream, the use of erodible banks is usually not considered practical because of the variations in the erodibility, shear strength characteristics, and groundwater conditions of the materials forming the banks of the natural stream. Also, reproducing the conditions in the model is difficult even if sufficient prototype data are available.[1,29,31,46] Using the river itself as a model can be useful if the increments constructed earlier are used to determine the reconstruction required to correct shortcomings in the earlier structures and to guide in designing subsequent improved structures. However, the trial-and-error field construction method often entails great expense, long delay, and limited success.[29]

23. Fukuoka and Yamamura[47] conducted full-scale model tests on instrumented embankments on the Yodo River in Japan. The test embankments were not subjected to river flow, but rather to artificial rainfall and static water level rise until shear failure occurred.

24. Based on observations of canal performances, allowable mean velocities have been estimated for canals in various soil types. Table 4 presents values of nonscour velocities as a function of soil density and canal depth for both noncohesive and cohesive soils.[48]

25. Research conducted by the Bureau of Reclamation[49] has resulted in correlations between tractive force and soil properties. Figure 15 shows the permissible tractive force versus particle diameter for cohesionless soils.[49] The relation between permissible tractive force and void ratio for cohesive soils is shown in Figure 16. A study[49] of undisturbed soil samples from test reaches of canals revealed the



CURVE A, FOR AVERAGE PARTICLE SIZE, WITH HIGH CONTENT OF FINE SEDIMENT IN THE WATER, FOR FINE BED MATERIAL; CURVE B, FOR AVERAGE PARTICLE SIZE, WITH LOW CONTENT OF FINE SEDIMENT IN THE WATER, FOR FINE BED MATERIAL; CURVE C, FOR AVERAGE PARTICLE SIZE, WITH CLEAR WATER, FINE BED MATERIAL; CURVE D, FOR SIZE OF PARTICLE SUCH THAT 25 PERCENT OF PARTICLES ARE LARGER, WITH COARSE BED MATERIAL.

Figure 15. Permissible unit tractive force versus particle diameter for channel beds in cohesionless soils (Reference 49)

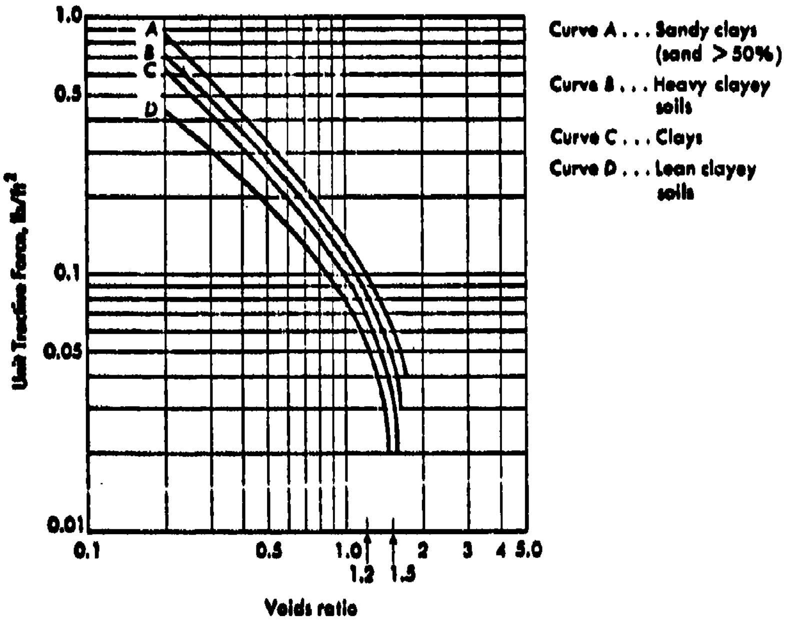


Figure 16. Permissible unit tractive force versus void ratio for channel beds in cohesive soils (Reference 49)

relation between critical tractive force (i.e. tractive force at the instant erosion noticeably began) obtained from laboratory tests and the plasticity characteristics of the samples (Figure 17). Figure 18 shows the relation between plasticity and erosion characteristics of cohesive soils.[49] The use of the tractive force principle in cohesive soils has been limited by the lack of knowledge concerning the influence of various parameters on erodibility.[50-52]

26. Schroeder[53,54] classified 121 natural and artificial channels in Nebraska and Iowa according to stability and percent density of vegetative cover. Tractive forces for each test reach were computed using the mean annual peak discharge. Figures 19 and 20 show the curves obtained for limiting bed and bank tractive forces, respectively, versus plasticity index and mean grain size for the ephemeral streams studied.

27. Schumn's relation[33] of width-depth ratio versus percent silt-clay in banks and channels as a stability criterion for ephemeral streams is given in Figure 11. Flaxman's relation[42] for channel

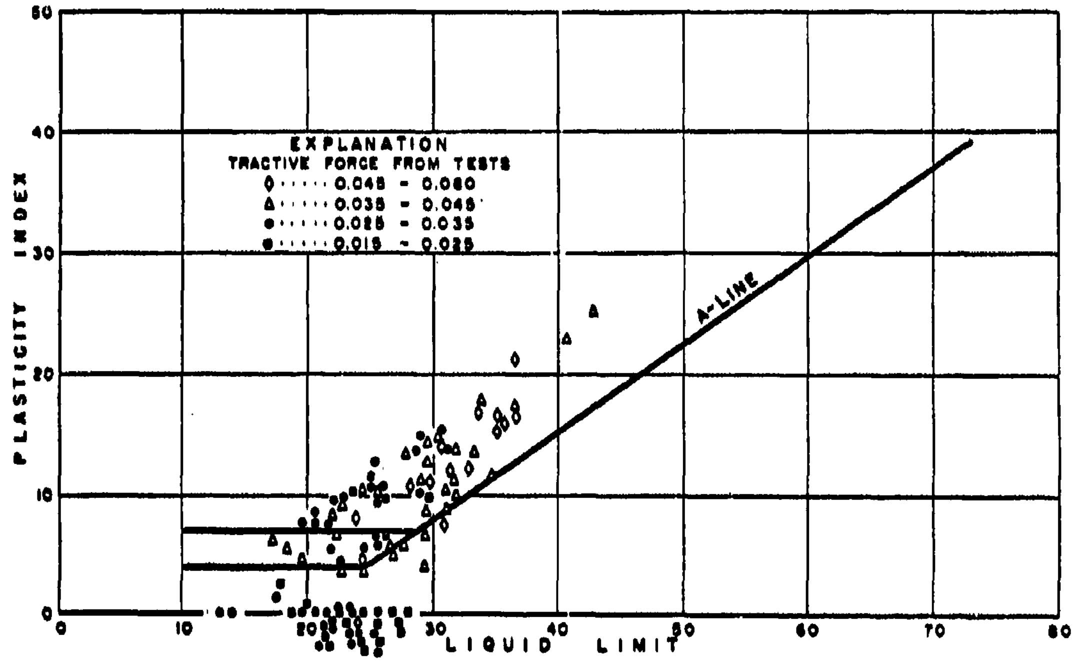


Figure 17. Critical tractive force obtained from laboratory tests and plasticity characteristics of samples (Reference 49)

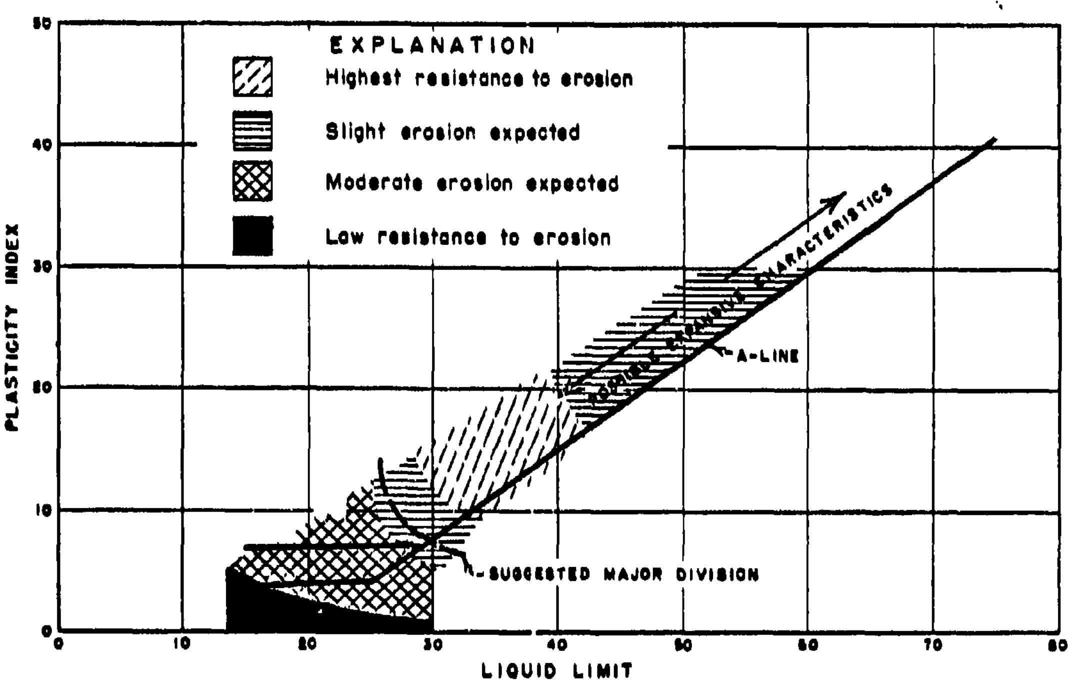


Figure 18. Relationship between plasticity and erosion characteristics (Reference 49)

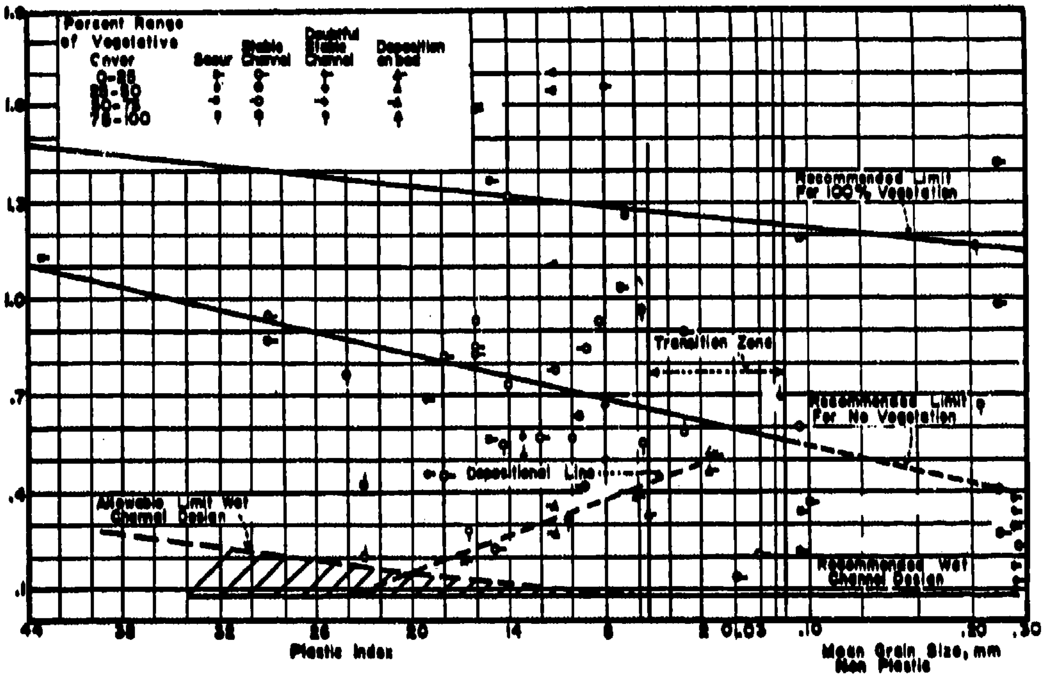


Figure 19. Limiting channel bed tractive force for ephemeral streams (References 53 and 54)

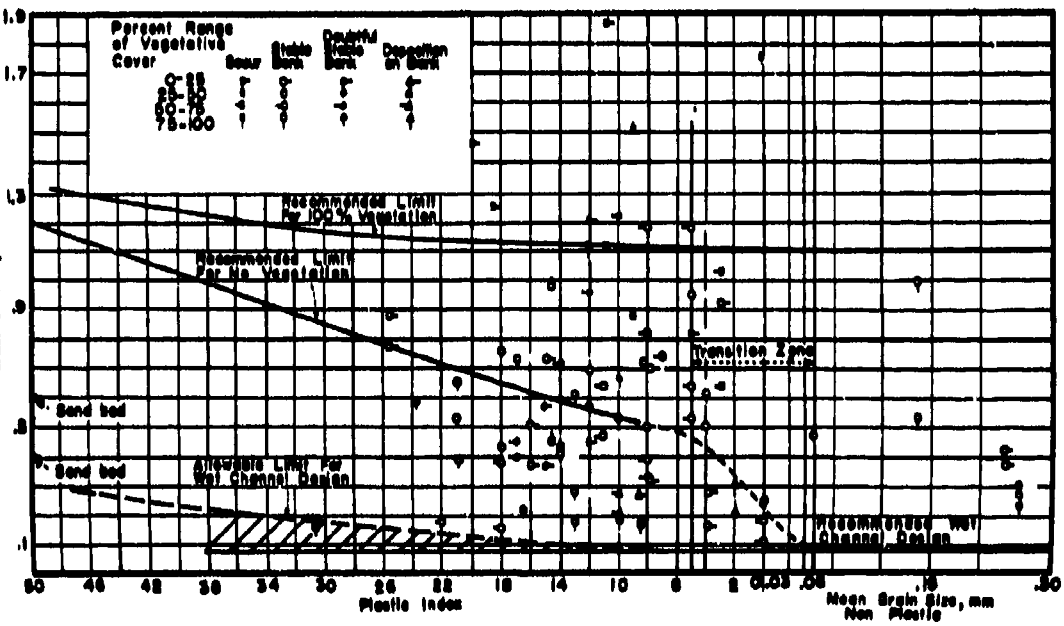


Figure 20. Limiting channel bank tractive force for ephemeral streams (References 53 and 54)

stability as a function of tractive power and unconfined compressive strength is given in Figure 14.

28. Strand[55] used field observations of and data collected from four noneroding test sections of a tributary of the Middle Loup River in central Nebraska to evaluate four criteria used in the design of stable channels in cohesive soils. According to Schumn's relation[33] for width-depth ratio versus percent silt-clay in banks and channel, the test sections are of the type tending to aggrade as shown in Figure 21.[55] Figures 22 and 23 (Reference 55) show that the test sections studied plot within Schroeder's[54] recommended limit for 100 percent vegetative cover. The banks on the test sections were generally well covered with vegetation. Strand[55] noted that other channel studies have disproved portions of the curves shown in Figures 22 and 23. Figure 24 (Reference 55), using Flaxman's relation[42] for tractive power versus unconfined compressive strength, shows that the test sections would be stable for the mean annual flood peak discharge.

Soil Mechanics Aspects of Streambank Stability

29. Although the general types of alluvial deposits are limited in number, there are so many variations in the conditions of deposition and subsequent erosion within the individual types that it is questionable whether two localities could be found in which any appreciable amounts of sediments are exactly similar in character.[22,56] The variation in depositional environment, coupled with the long reaches usually involved in streambank stability, makes it impractical to conduct detailed soil and groundwater investigations that would otherwise be justified for the foundation design of structures such as locks or dams. Therefore, to determine which areas require more detailed investigations because of unfavorable soil and groundwater conditions, it is imperative to utilize any existing geologic and soils data on the soils in the area of interest and to supplement this information with limited subsurface exploration and laboratory testing.[29]

30. The erosive characteristics of cohesionless soils, which are

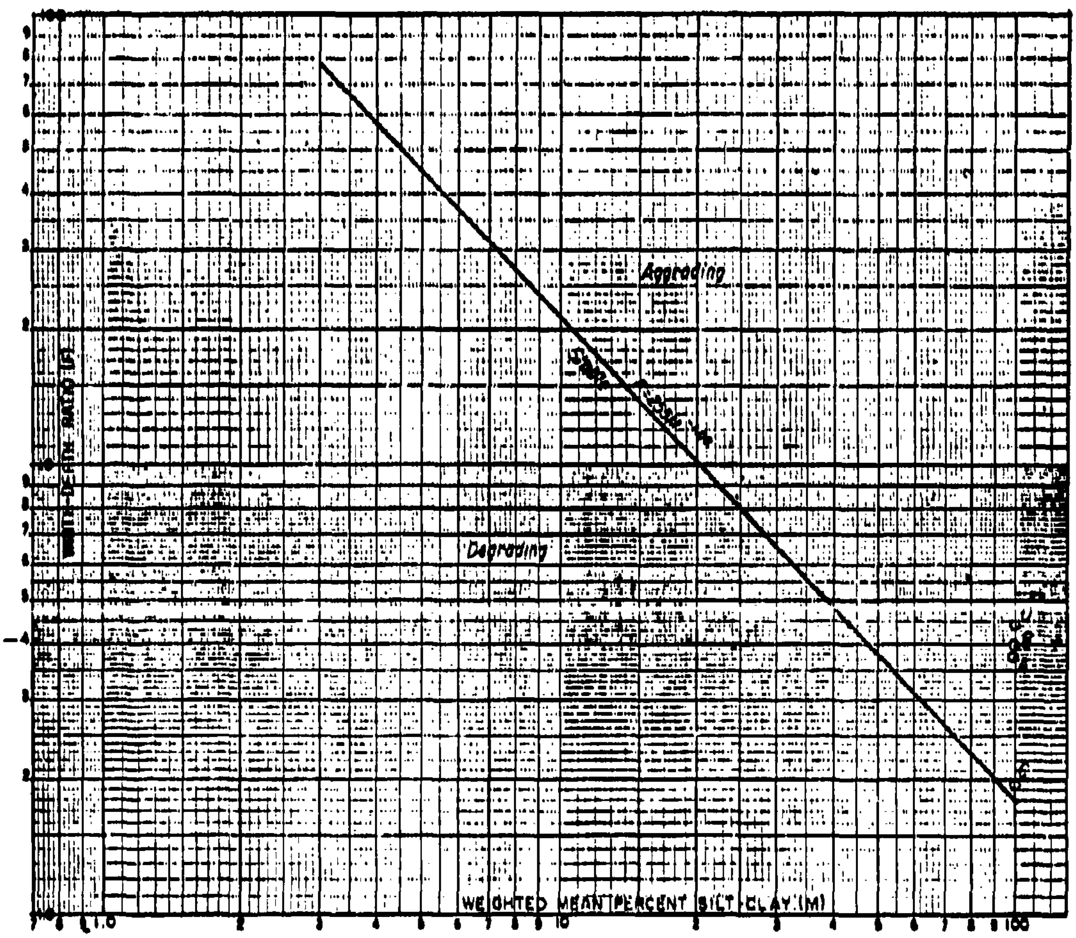


Figure 21. Evaluation of channel stability of Middle Loup River, Nebraska, using Schumn's relation[33] for width-depth ratio versus percent silt-clay (Reference 55)

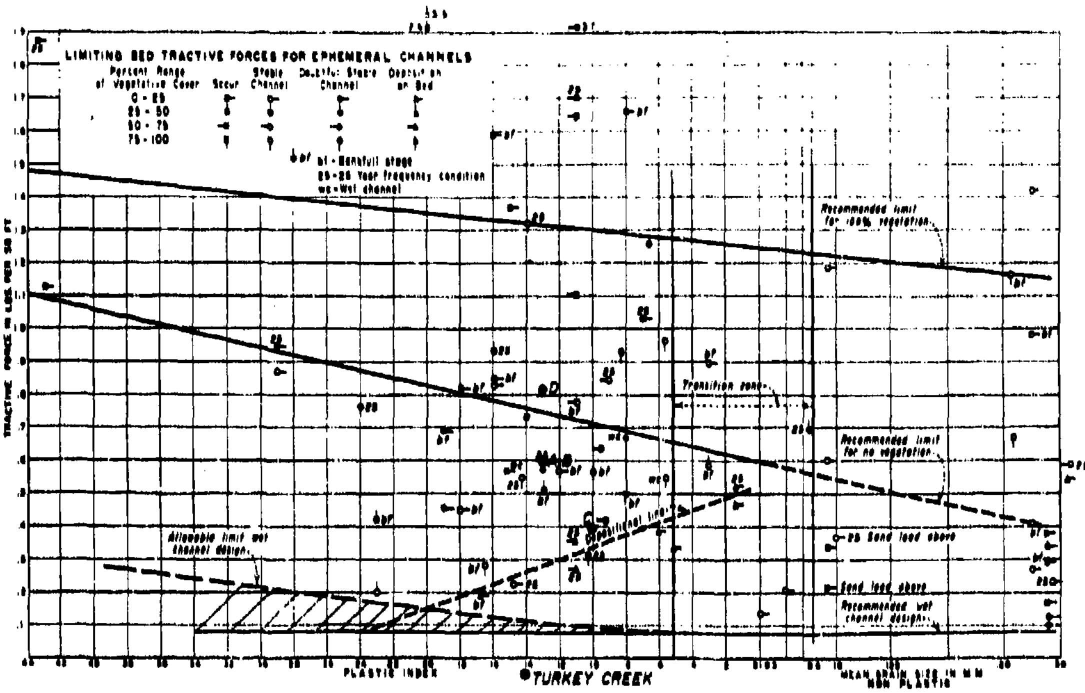


Figure 22. Evaluation of channel bed stability of Middle Loup River, Nebraska, using Schroeder's relation[54] for bed tractive force versus plasticity index (Reference 55)

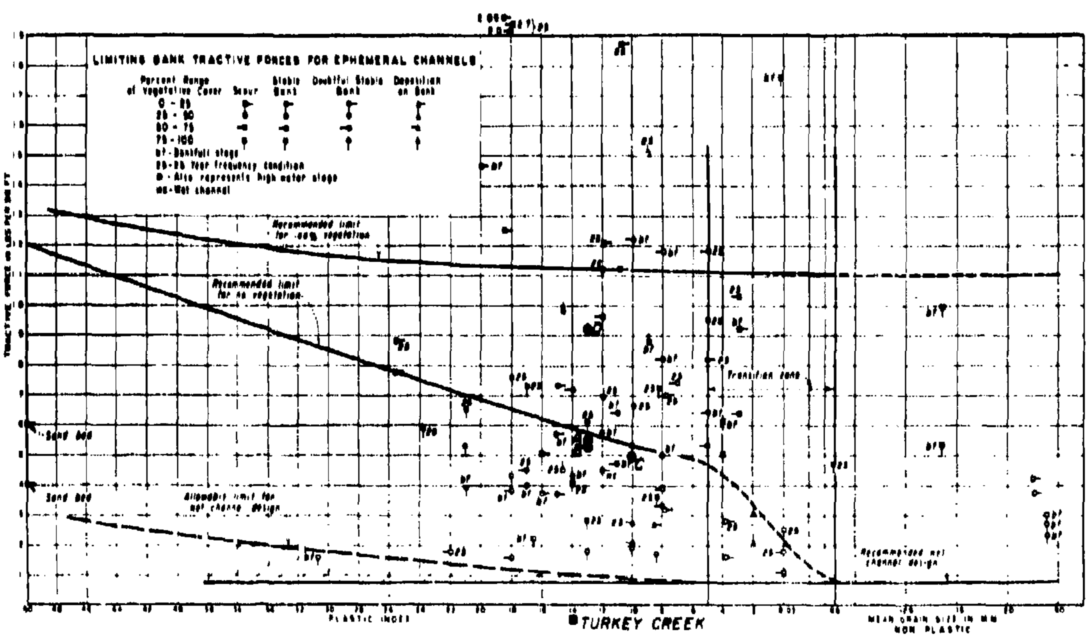


Figure 23. Evaluation of channel bank stability of Middle Loup River, Nebraska, using Schroder's relation[54] for bank tractive force versus plasticity index (Reference 55)

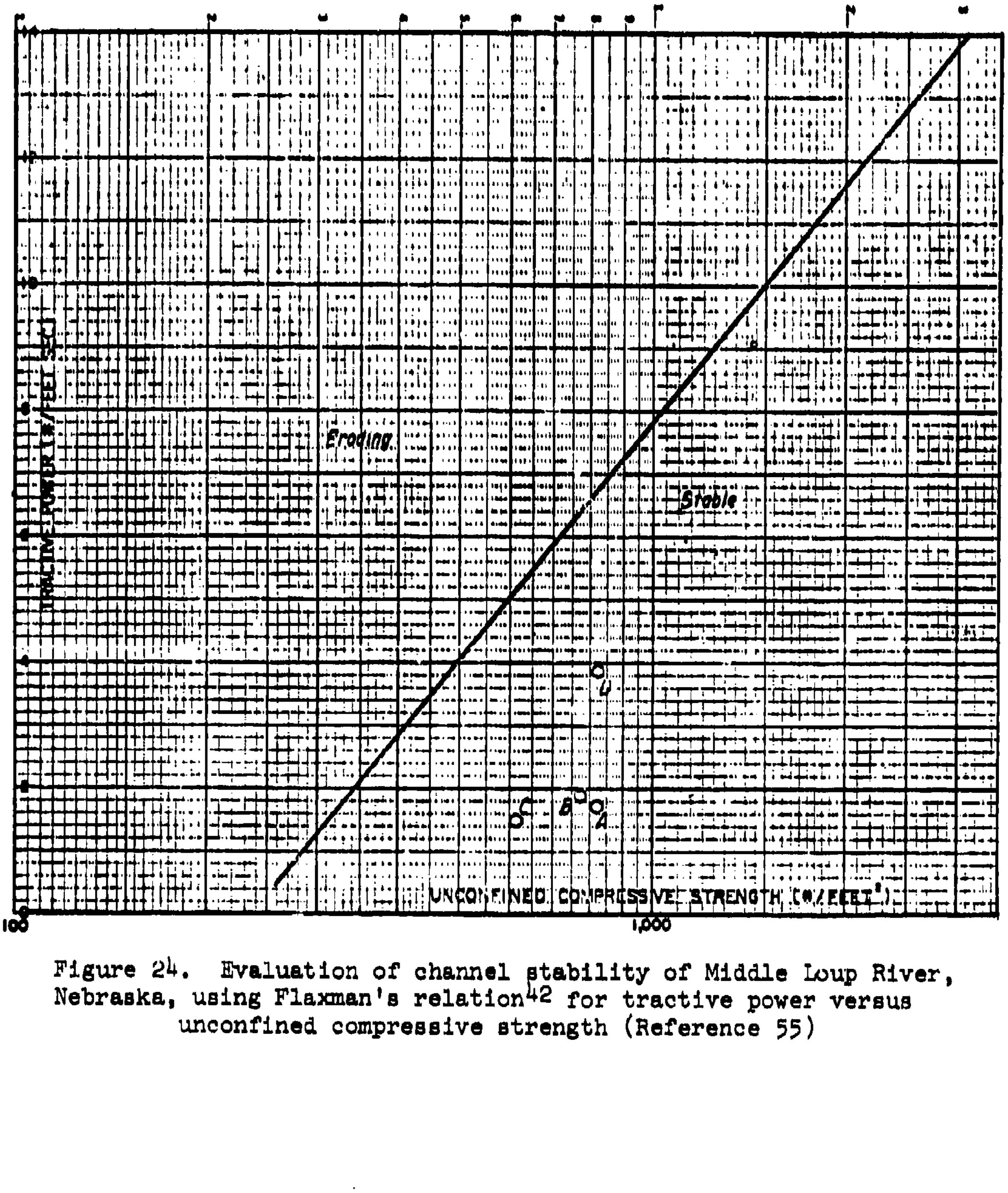


Figure 24. Evaluation of channel stability of Middle Loup River, Nebraska, using Flaxman's relation[42] for tractive power versus unconfined compressive strength (Reference 55)

controlled by gravitational forces, and the basic parameters affecting the erosion of cohesionless soils (particle size, grain shape, gradation, moisture content, and relative density) are fairly well understood.[57] However, the development of a quantitative procedure for streambank stability analysis has been stymied, in part, by a lack of understanding of the erosive characteristics of cohesive soils, which are controlled by physical and electrical surface phenomena.[52,53,55-61] However, an understanding of the erosive process in cohesive soils has advanced considerably during the past decade.[51] The basic parameters affecting the erosion of cohesive soils are soil pore-water concentration (type and amount of cations), composition of soil (percentages of sand, silt, and clay), type and amount of clay mineral, moisture content, dry unit weight, soil pH, eroding fluid composition (type and amount of cations), eroding fluid pH, and temperature of eroding fluid. Both the flume erosion test[53,62-67] and the rotating cylinder apparatus[51,53,58-62] have been used to determine the rate of erosion versus applied shear stress for cohesive soils. Flume erosion tests have recently been conducted to determine the critical shear stress on remolded samples of bed material in connection with a study to determine whether armoring was required when groins were placed in the Rhine River.[68]

31. Figure 25 shows a quantitative procedure for streambank stability analysis. Such a procedure could be utilized to determine bank recession with time for a selected stream. This information could then be used in planning and designing streambank protection for the stream.[69,70]

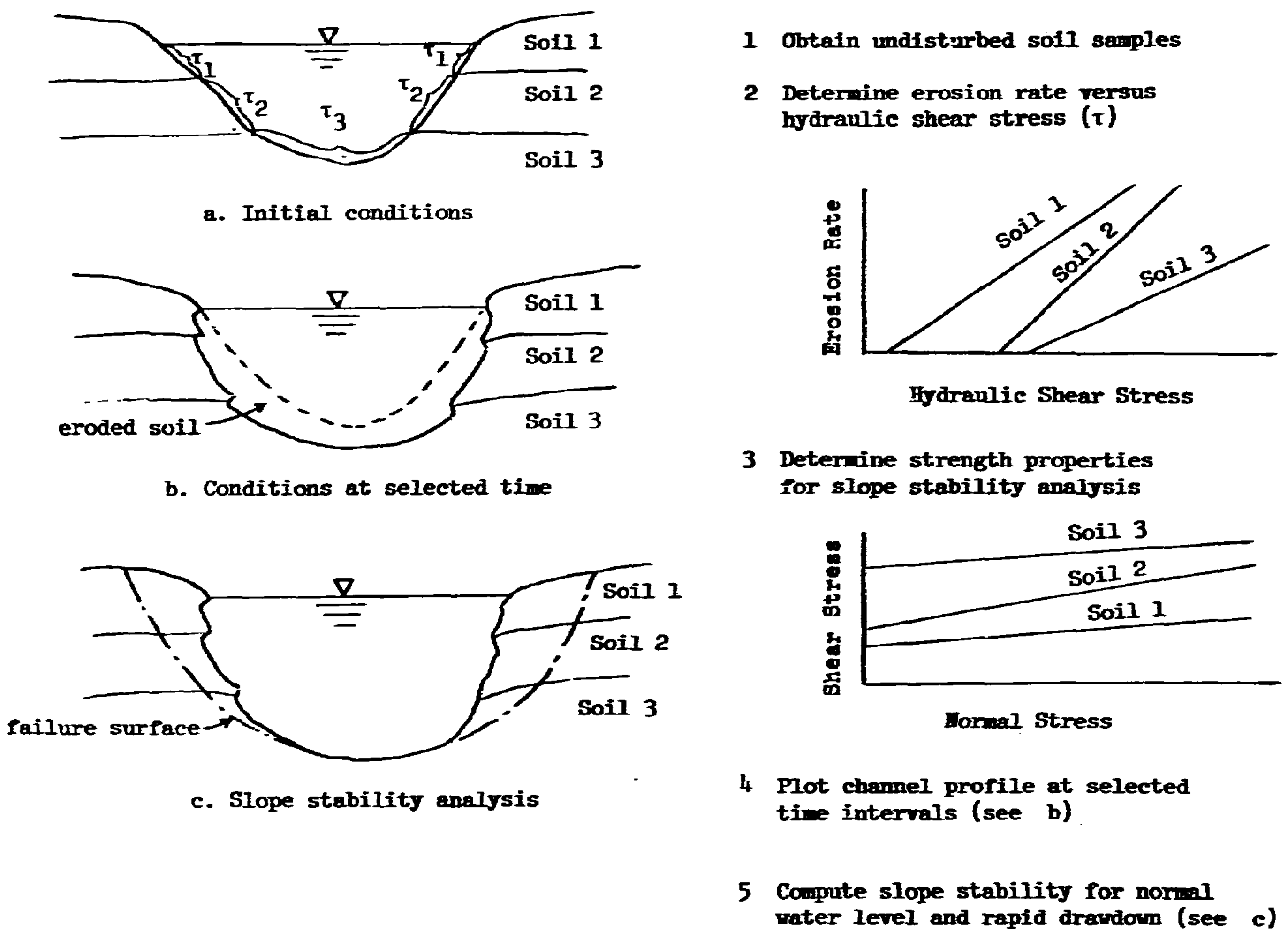


Figure 25. Procedure for streambank stability analysis

PART IV: PRELIMINARY ASSESSMENT OF STREAMBANK PROTECTION METHODS

32. Effective protection of streambanks along the navigable waterways of the United States is an integral part of the Corps of Engineers responsibility to maintain navigation channels, protect property, and improve water quality. A variety of experiments have been conducted to determine the most effective and economical bank protection "methods" (paragraph 6) for various areas; however, no specific guidelines have resulted that can be used to assist the engineer in developing design specifications for a particular bank protection problem. What has developed is the use of a group of methods that has found subjective favor in the engineering community. The most widely used of these are:

- a. Stone riprap.
- b. Concrete pavement.
- c. Articulated concrete mattresses.
- d. Transverse dikes.
- e. Fences.
- f. Asphalt mix.
- g. Jacks.
- h. Vegetation.
- i. Gabions.
- j. Erosion-control matting.
- k. Bulkheads.

The use and effectiveness of each of these are discussed in the following paragraphs using information derived from the references listed in Appendix D. In addition, several other methods are discussed that are not used on a widespread basis.

Stone Riprap

33. Riprap consists of rock courses placed along the bank to be protected (Figure 26). Prior to placement, the bank is usually graded if the slope is irregular. A bed of gravel or porous filter material is

Figure 26. Riprap placement

then placed over the graded bank to allow seepage but prevent erosion of the bank material. Where stones of sufficient size are available, riprap is usually the first choice among the bank protection methods considered because of the following general advantages:

- <u>a</u>. A riprap blanket is flexible and is neither impaired nor weakened by slight movement of the bank resulting from settlement or other minor adjustments.
- <u>b</u>. Local damage or loss is easily repaired by the placement of more rock.
- <u>c</u>. Construction is not complicated and no special equipment or construction practices are necessary.
- <u>d</u>. Appearance is natural, hence acceptable in recreational areas.
- <u>e</u>. If riprap is exposed to fresh water, vegetation will often grow through the rocks adding structural value to the bank material and restoring natural roughness.
- <u>f</u>. Riprap is recoverable and may be stockpiled for future use.

34. The effectiveness of a riprap blanket is evaluated in terms of the stability of the blanket under the influence of excessive hydraulic flow conditions, the ability of the bedding material to prevent the erosion of the natural bank material through the riprap, and resistance to undercutting and raveling at the ends of the blanket. Meeting the design objectives necessary to guarantee effective bank protection requires (a) determination of the shape, size, and weight of the stones in the riprap blanket that will be stable under excessive hydraulic flow conditions; (b) well-graded bedding material or filter cloth that will prevent erosion of the bank material through the blanket; (c) optimum blanket and bed thickness; and (d) proper termination of the riprap blanket.

35. Several empirical relations have been developed, using Airy's law, to determine the minimum stone size and weight that will be stable for the maximum hydraulic flow that will occur along the bank to be protected.[71] When the size and weight are determined, the values are usually interpreted as a median value, i.e., 50 percent of the stones used in the blanket must have diameters greater than the computed median

diameter, and no more than 50 percent of the stone can weigh less than the computed median weight. No analytical method has been developed to determine the optimum stone shape; the selection of the stone shape is usually a compromise between subjective experience and what is available. Elongated stones are generally rejected in favor of "block-type" stones because they fit together better. Sharp edges are preferred over rounded edges for increased stability. In general, no stones should be used with length-to-width ratios greater than 3 and no more than 25 percent of the stones should have a length-to-width ratio greater than 2.5.

36. Both quarry-run and graded stone are used for riprap placement. Large stones are usually eliminated by the contractor; these stones should be removed from the blanket or broken up because accelerated water flow around a large stone can cause scour as well as removal of small stones adjacent to the large one. Poor gradation may also encourage riprap blanket failure because oversize stones may preclude mutual mechanical support among individual stones. If the gradation of riprap is such that movement of the underlying natural material through the blanket is likely, a filter bed of sand, crushed rock, gravel, or synthetic cloth (Figure 27) must be placed under the stone blanket. An ideal riprap blanket design would provide a gradual reduction in stone size until the stone of the blanket blends with the natural bed material; however, this is seldom economically justified. The stability of the riprap blanket is sometimes improved by grouting the stones; however, this technique reduces the permeability of the bank, which may lead to revetment failure due to hydrostatic pressure under the blanket.

37. The thickness of a riprap blanket should be at least 1 to 1.5 times the maximum diameter of the largest stones used in the blanket or twice the average diameter of the stones used. The recommended maximum bank slope for dumped stone is 1V on 2H. The maximum slope can be increased to 1V on 1.5H for hand-emplaced stone.

38. Riprap has been used effectively in channel stabilization and realignment efforts using the "trench-fill" technique (Figure 28). This approach requires that the bank be graded to conform to the desired channel configuration. A trench is excavated at the base of the graded

Figure 27. Installation of filter cloth prior to placement of riprap (photo courtesy of the Erosion Control Division, Carthage Mills, Inc.)

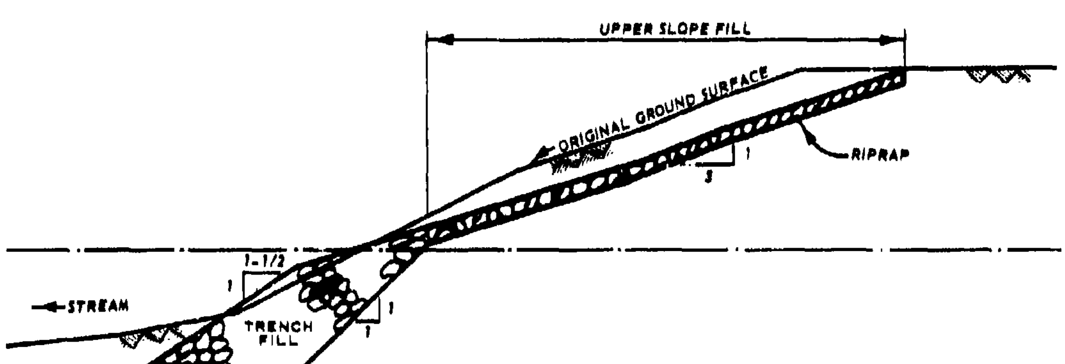


Figure 28. Trench-fill revetment

bank and filled with riprap as shown in Figure 28. Additional riprap is placed on the graded bank above the trench. As the erosive action of the stream acts on the bank between the stream and the trench, the bank fails, and eventually the trench becomes the revetment.

39. In-place cost of a stone riprap blanket (Table 5*), including bank preparation, bedding material, and transportation of stone, can vary greatly depending on the location and availability of suitable rock. The current estimate for average in-place cost (1976) ranges from $\$3.50/yd^3$ in an area where stone is readily available to $\$30.00/yd^3$ in a metropolitan area where stone must be hauled over long distances.

40. The majority of theoretical design work related to streambank protection works has been directed toward riprap. A review of available literature indicates that the riprap studies have yet to be consolidated into a straightforward design procedure that a field engineer can confidently use; however, Engineer Manuals[71-73] can provide limited design guidance. Also, experience can be gained in on-site work and physical model studies.

Concrete Pavement

41. Concrete pavement is generally an expensive bank protection method because forms must be constructed and concrete mix design, batching, and curing must be rigidly controlled. However, use of concrete pavement provides a high degree of reliability over a long life with a minimum of maintenance (Figure 29). The only major problem results from scour under the slabs due to inadequate subsurface drainage; deterioration of the concrete slab itself is rarely significant. Pavement is used along banks, bridge abutments, and main-line levees in heavily populated or industrialized areas where a large safety factor is required. In-place cost (1976) for concrete pavement, including bank preparation and construction of forms, ranges from \$90 to \$125 per 100 ft^2 (Table 5).

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* Table 5 summarizes 1976 costs for all methods discussed in this part. Cost figures in this report were supplied by Corps of Engineers Divisions and Districts.

Figure 29. Concrete pavement bank protection

Articulated Concrete Mattresses

42. The development of articulated concrete mattresses (Figure 30) began in 1914 chiefly as a result of the threatened exhaustion of convenient willow growths from which timber and brush mattresses had previously been constructed. Since termination of experiments with bituminous mattresses in 1945 (paragraph 60), concrete mattresses have been used almost exclusively for subaqueous revetment on the lower Mississippi River. An articulated concrete mattress, because of its weight and flexibility, is an effective performer on parts of the bank that are subject to excessive hydraulic flow conditions. Because of the specialized construction equipment required, use of this method cannot be economically justified for small streams except those close to the Mississippi River where the mattresses can be delivered to the construction site by truck or barge.

43. The basic unit of the mattress is a slab of concrete 3 ft 10-1/4 in. long by 14 in. wide by 3 in. thick. These slabs are cast on and tied together by corrosion-resistant reinforcement wire to form rectangular units 4 ft wide by 25 ft long when allowance is made for the

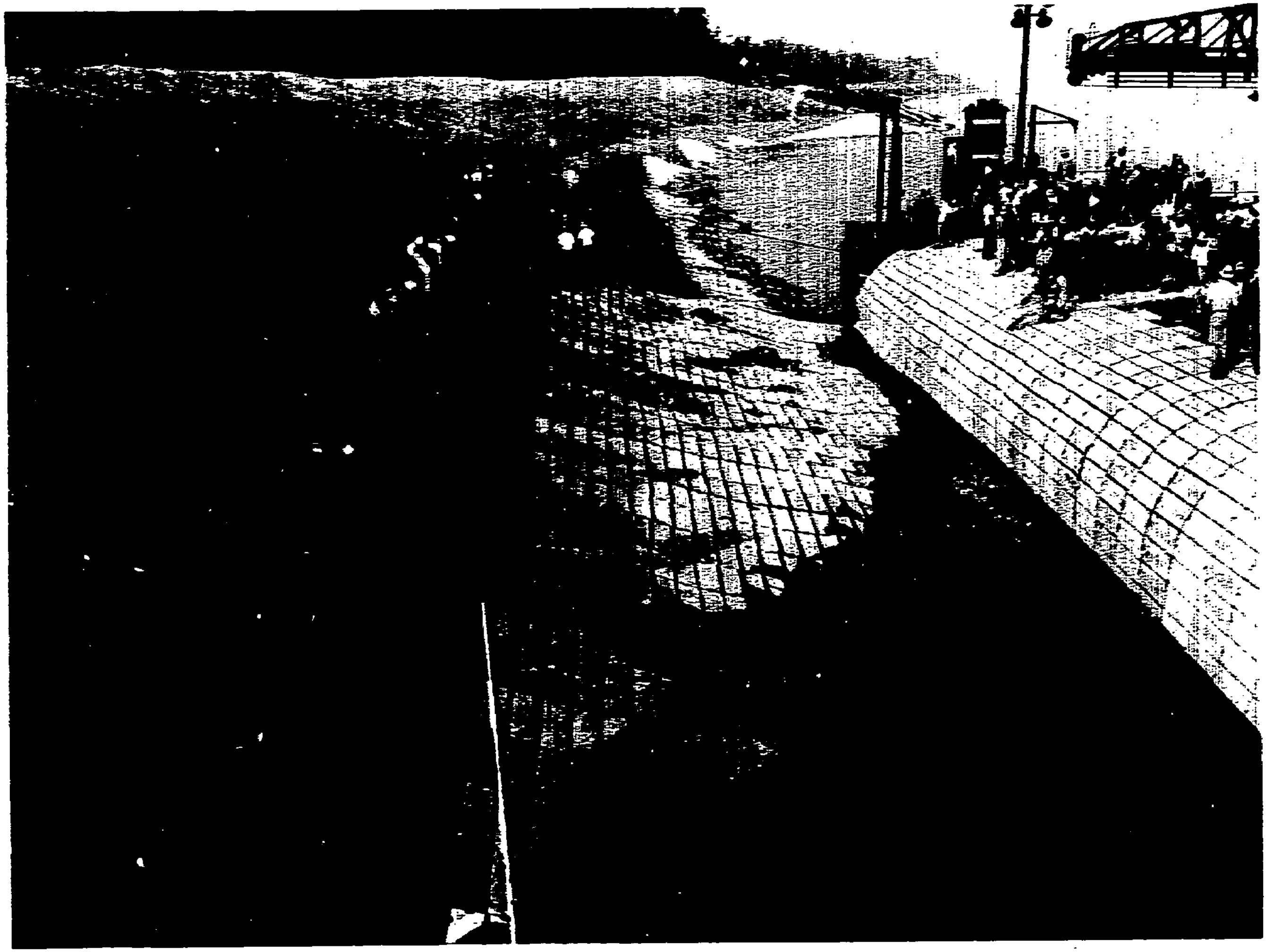


Figure 30. Articulated concrete mattress being sunk from launching barge

1-in. space between the slabs and for the space between adjacent rectangles. These units are commonly called "squares." Because a mattress is made up of squares connected by articulated joints, it possesses a measure of flexibility in all directions. Thus a mattress has the capability of adjusting itself to irregularities in the bank and to scour pockets that may develop. The principal disadvantage of the concrete mattress is the possibility of bank material eroding and escaping through the interstices of the articulated joints.

44. Articulated concrete mattresses with the ends and sides of the slabs notched in a "V" shape (designated a V-type mattress) were developed to reduce the size of the interstices. This design reduced the openings from about 10 percent of the total mattress surface area to 1 percent. Subsequent surveys conducted over a period of several years indicate that the V-type mattresses sank very little because of bank materials washing through the interstices.

45. After the submerged bank has been shaped in preparation for placement of a mattress, the squares are assembled on a launching barge that is anchored over the underwater bank. A mattress up to 140 ft wide, measured parallel to the bank, is assembled by placing the squares side by side on the launching barge and connecting them with corrosion-resistant wire and clamps (Figure 30). When the squares have been assembled into a 25- by 140-ft unit, the configuration is termed a "launch." After the launch has been assembled and connected to successive launches, the completed mattress is moved off the barge and sunk in place on the underwater bank by securing the mattress to the bank and moving the barge toward midstream.

46. Shaping of subaqueous banks and mat sinking operations are not commenced until the river stage has fallen to 15 ft above mean low water. Normally, if a sustained rise above 15 ft is in prospect, these operations are suspended. The restriction of river stage on operations limits revetment placement to the low-water season usually between mid-July and mid-December. In emergencies, mattresses have been placed when the stage was as high as 25 ft above mean low-water stage, river currents and debris conditions permitting. The upper limit of concrete

subaqueous revetment is normally 6 ft above mean low water. The mattresses are laid into the river to a point 50 ft past the thalweg unless a lesser distance is specified. As of 1976 there were two mattress-sinking plants in operation on the lower Mississippi River, each designed to place a mattress 140 ft wide. Both of these units are capable of placing 10,000 squares per day. At this rate, approximately 20 bank miles of mattresses can be laid by each unit during a normal working period of five months, i.e. the low-water season. Average in-place cost (1976) of the articulated concrete mattress, including bank preparation, is $84 per square (100 ft^2) (Table 5).

47. Prior to 1940, squares were cast entirely on a floating plant. However, as the volume of work increased, it became apparent that this immobilized too many barges during the concrete curing period. To speed up the casting operations, land casting fields have been placed at convenient locations along the riverbanks. At this time (1976) there are seven land casting fields between Cairo and New Orleans having storage capacities ranging from 40,000 to 380,000 squares, which makes it possible to cast and store these units in the quantity necessary for normal demand (Figure 31). The production rate for the floating casting

Figure 31. Concrete squares stored at casting field

plant of 1931 was approximately 60 squares/hr. Steady improvement in field casting production efficiency has resulted in an increase from 100 squares/hr in 1948 to a maximum of 200 in 1970.

Transverse Dikes

48. Transverse dikes are considered to be an indirect method of bank protection, because eroding river currents are deflected away from the bank or reduced in velocity, as opposed to a direct method in which the bank is physically isolated from the eroding currents.

49. Transverse dikes are of two principal types, permeable and impermeable. The permeable type is effective in slowing the current over a portion of the channel area thereby causing deposition of sediment. The accumulation of sediment and the retardation of flow produced by a dike system cause the main channel section to carry a larger proportion of the water than it did in the absence of the dike system thereby increasing the current velocity and the sediment transport capacity. As a result, greater depth is maintained in the main channel. A permeable dike is most effective on a stream where the velocity is sufficient to carry a substantial load of coarse sediment that will settle as a result of a moderate reduction in current velocity. Impermeable dikes do not require sediment deposition to redirect the hydraulic flow. An impermeable dike simply reduces the width of the river, and the river, as it is contracted to a narrower channel, attempts to regain the cross-sectional area required to pass the same discharge as was passed before the dike field was put into place. When the bank opposite the dike field has become stable, the main flow begins to scour out the bed of the river, which produces an improved navigation channel. After the river has deepened enough to regain its normal cross-sectional area, the bottom scouring stops.

50. Timber piles are the basic components of most permeable dikes (Figure 32). Timber-pile dikes of various designs have been constructed using face boards with horizontal bracing, as well as single piles and clumps (three piles strapped together) in single or multiple rows. The

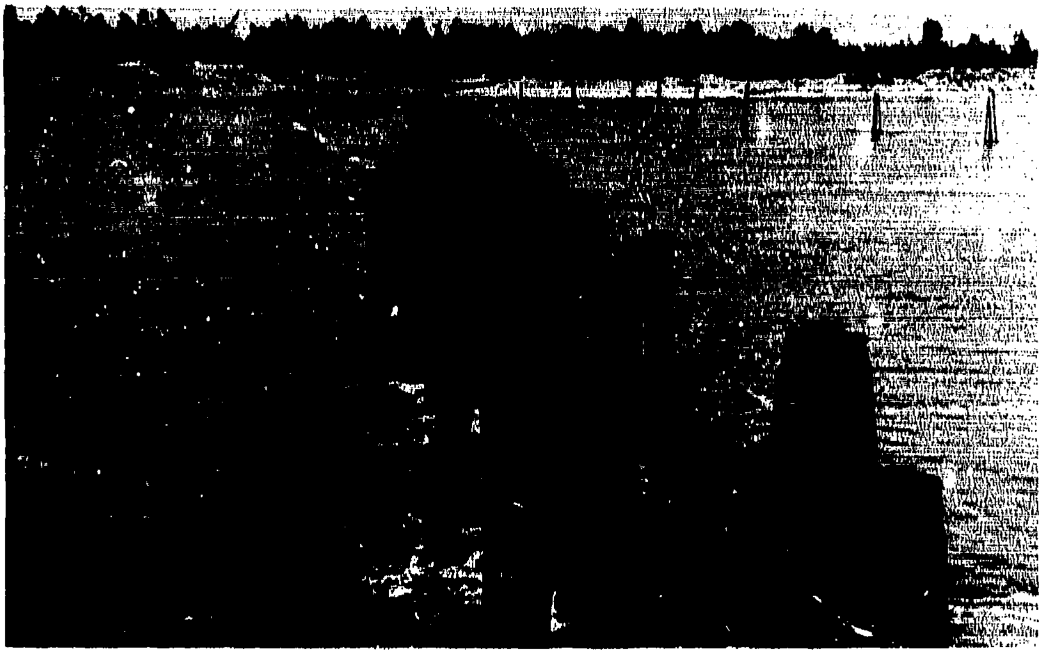


Figure 32. Timber-pile dike

design selected depends on the depth of the stream and the severity of the hydraulic flow conditions that must be sustained by the pile dike once it is in place. The spacing of the piles or clumps can be varied from one location to another in accordance with the quantity and character of the sediment transported. For example, very fine sand entrained by the water requires greater reduction in flow velocity to settle out than does coarser material, and as a result, closer spacing of the piles or clumps is needed. The permeability of pile dikes can be further reduced by suspending screens to encourage more complete and effective deposition. This technique is especially useful where the sediment movement is not great and the sediment contains fines that would otherwise not deposit.

51. Transverse stone dikes are now the most widely used impermeable dikes (Figure 33). They are usually constructed from quarry-run stone with specified limitations on the maximum size of stone and amount of fines. These dikes are built with crowns of various widths up to 10 ft or more, depending on the severity of the expected attack, the

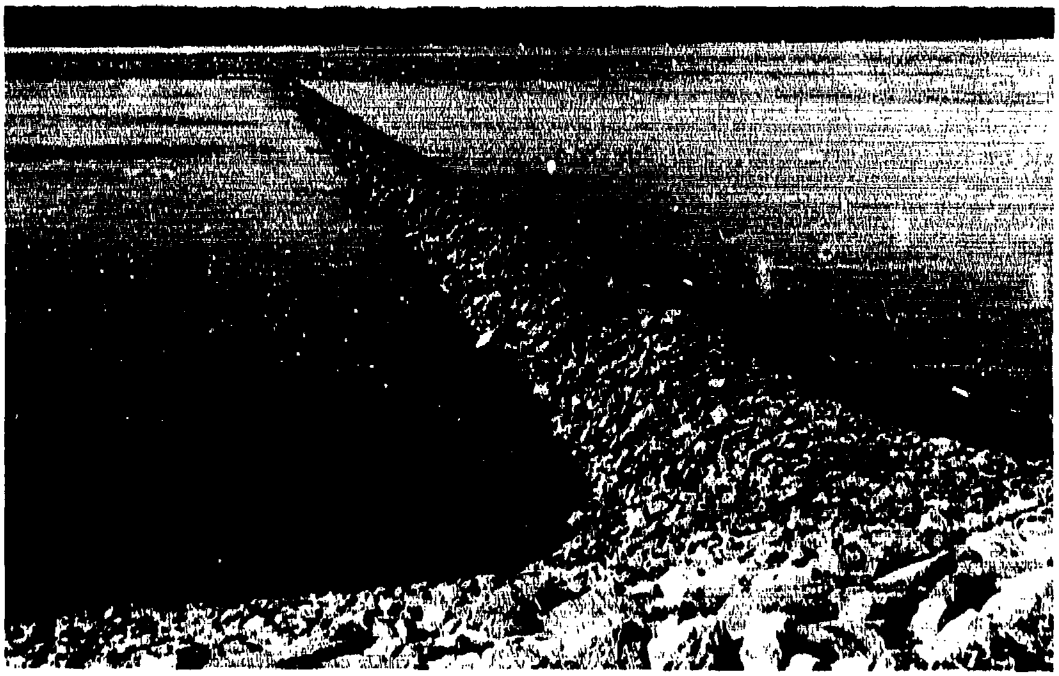


Figure 33. Transverse stone dike

method of construction, and the requirements for maintenance. The principal mechanical advantage in using stone is that a dike can be constructed so that the void volume is minimized and little or no water passes through. Thus, when used for channel contraction or bank protection purposes, impermeable dikes do not require the deposition of sediment in the dike field to as great an extent as do the permeable dikes. Nevertheless, sediment between the dikes is necessary to make the contraction or protection continuous along the dike field and to reduce the scalloping of the banks between the dikes that may be caused by eddies and overtopping flow.

52. In general, transverse dikes extend into the stream past the point where the highest velocities occur. This function is to move the thalweg from its position along an eroding bank to an alignment controlled by the location of the structures.

53. When the principal purpose of transverse stone or pile dikes is bank protection, they are sited uniformly along caving banks based on the following considerations. The spacing between any two dikes has

generally been related to the average of their lengths multiplied by a spacing-length ratio. The spacing-length ratio is derived from the experience of the designer. The final selection of spacing and length may be an economic one, but for bank protection purposes, the length of the dikes should be just sufficient to move the eroding current away from the bank. Of course, there is a limitation on length since it must not be such that the dike will unduly restrict the navigation channel or increase the current velocity to an unacceptable value.

54. The average construction cost of pile board dikes is $40 to $55/lin ft (1976). Untreated pile clumps (three 60-ft piles to a clump) range in cost from $1500 to $2300 each (1976). Transverse stone dikes range in cost from $40 to $65/lin ft (1976) (Table 5).

Fences

55. Wire fences are used to solve a variety of bank protection problems on low-gradient streams with discharges less than 500,000 cfs. Fences can be positioned parallel to the bank (Figure 34) as well as

Figure 34. Wooden fence constructed parallel to bank

Figure 35. Wire fences constructed transverse to streamflow

transverse to the streamflow (Figure 35). Two fences parallel to the bank are sometimes constructed 3 to 10 ft apart. Brush, hay, or rock is stacked between the fences, providing an extra measure of protection against the erosive action of the water currents. If the fences are constructed parallel to the bank and the bank is steep enough, a second fence is not required for holding the brush backfill. Fences constructed parallel to the bank generally serve as an erosion stopgap measure to allow sufficient time for the establishment of vegetation or to prevent sloughing of the bank. Fences constructed across part of the stream section promote sediment deposition. A transverse fence can be positioned to deflect debris downstream or to trap it. By constructing the fence so that it is oriented downstream at an oblique angle to the current flow, debris will be deflected into the main channel. This technique is useful if the stream has a heavy debris load and the designer desires to keep the banks clear. Conversely, the fence can be constructed so that it is oriented upstream at an oblique angle to the current flow. Debris is then trapped behind the fence. This construction method is effective for clearing the main channel of debris and serves to encourage sediment deposition.

56. Many types of local materials can be used for fence construction. The fence posts can be of treated or untreated wood, used rails,

pipe steel beams, or concrete. Additional supporting members for the posts can be constructed of the same materials. The fencing material is generally wood or wire. If wire is used, the required tensile strength depends on the design loading by the water and debris. Field fencing and welded-wire fencing are effective for heavy and medium loading and chicken wire, for light loading.

57. Fencing is not considered to be one of the most effective means of bank protection, but it is commonly used because no special techniques are required for construction and there is a wide availability of materials suitable for assembly of the fences. Installed cost of the fencing is \$25 to \$50/lin ft (1976) if all material must be purchased new (Table 5); the cost is substantially reduced by the use of secondhand or free materials that are commonly available in rural areas.

Asphalt Mix

58. Asphalt mix has been used in several ways to provide bank protection--as blocks, reinforced mattresses, or uncompacted on an upper bank.

59. Asphalt blocks were used in 1918 and again in 1951 as a substitute for ballasting stone and riprap on the lower Mississippi River below Natchez, Mississippi. Quality stone for riprap is not widely available in this region and must be transported from several hundred miles away, but river sand and petroleum products (essential ingredients of asphalt blocks) are available. The casting and dumping of asphalt blocks proved to be uneconomical for use as ballast or riprap in 1918 and in 1951 as compared with using imported stone. Since 1951, only minor placement and evaluation have been done to investigate the effectiveness of asphalt blocks for constructing bank protection works. Further investigation based on current market values may be warranted.

60. Another type of asphaltic bank protection was used on the lower Mississippi River from 1934 to 1945. Compacted, cable-reinforced mattresses (commonly called bituminous mattresses) were laid on the

shaped riverbank below the low-water line. Most protection of this type was below Baton Rouge, Louisiana, where the bituminous mattresses were placed over timber or old willow mattresses as reinforcement against bank failure (Figure 36). The reinforced, compacted bituminous

Figure 36. Bituminous mattress placed over timber mattress

mattresses were designed to have many of the necessary features of an effective subaqueous mattress. They were continuous, impermeable, fairly flexible, and resistant to abrasion; unfortunately, many failures occurred. The impermeability of a bituminous mattress rendered sinking impossible in currents greater than 5 fps. Even though holes were drilled in the mattress, it acted much like a flag in the breeze. Eventually, the mattress would tear or fold over downstream. Although specifications called for a flexibility superior to that required for highway pavements, the mattresses could not withstand the constant flapping, bending, and folding that occurred at many locations. Low-water inspections indicated that the mattresses did not conform very well to changes in the channel geometry. This resulted in sections

Figure 37. Failure of bituminous mattress

breaking away leaving only exposed cable (Figure 37). Other problems resulted from failure of the works at exposed ends and at the connection between the mattresses and the upper bank works. Serious problems also occurred when the impermeable mattresses restricted the natural bank drainage. The increased pressure differential eventually caused failures at weak points in the mattresses ("blow holes"). The mechanically sophisticated plant required to lay the mattresses and the high frequency of failures made the cost of this protection method exceed that of articulated concrete mattresses (paragraphs 42-47). Efforts to place bituminous mattresses were terminated in 1945.

61. The use of uncompacted bulk asphalt mix dumped from trucks (Figure 38) or spreaders (Figure 39) on upper banks has proved to be successful. Bulk asphalt mixes have been in common use since 1945.

62. The mix used for upper bank revetments generally consists of river bar sand and 6 percent, by weight, of 85-100 penetration asphalt. The sand is obtained from the nearest or most accessible bar in the

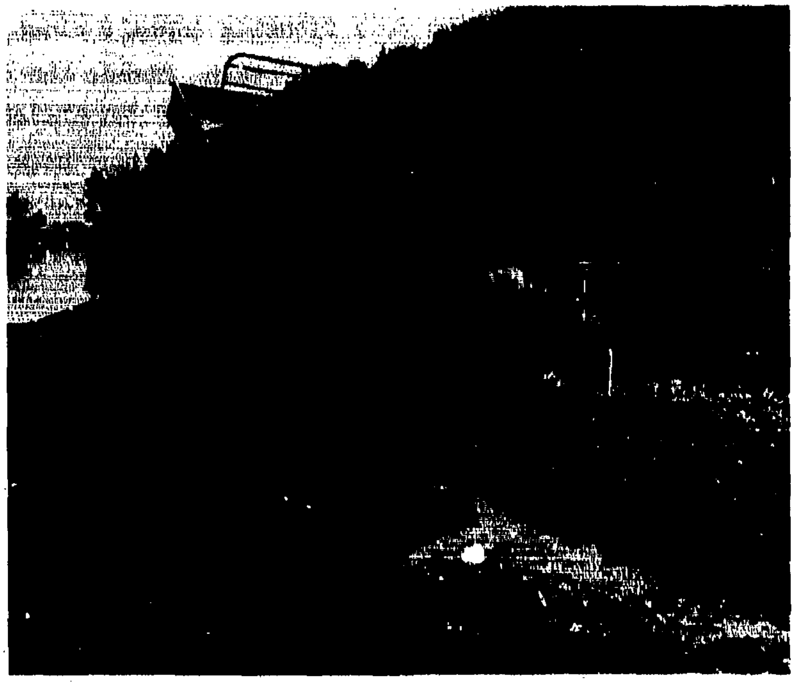


Figure 38. Bulk asphalt dumped from truck onto upper bank (photo courtesy of Royal Dutch Shell)

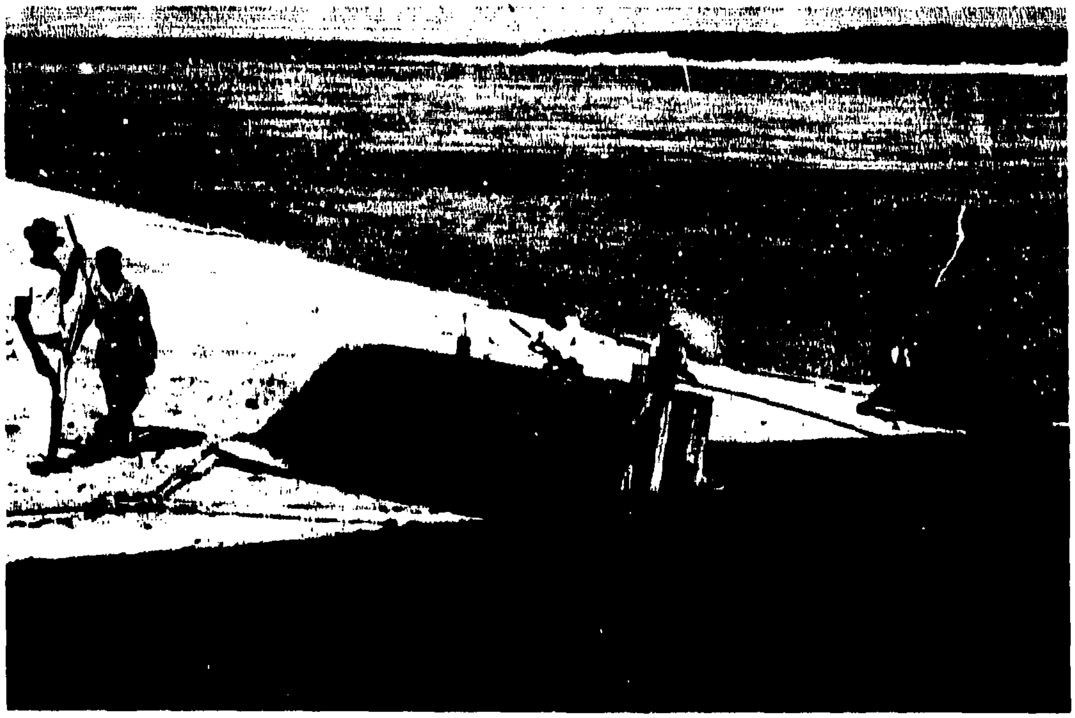


Figure 39. Spreader placing asphalt mix on upper bank

river and is transported by barge to a floating asphalt plant where it is dried and mixed with the asphalt. After being mixed, the material is picked up from the discharge bin with a clam bucket and placed in a dump truck or pull-type spreader box on the lower edge of the bank to be paved. A tractor at the top of the bank pulls the spreader slowly up the bank with a winch. In this manner, a nominal 5-in.-thick layer of sand-asphalt is placed on the previously graded bank and left in an uncompacted condition. (The banks are usually graded to a 1V on 3H slope.) This technique has been satisfactory where floodwater velocities have not exceeded 7 fps. Above this velocity, excessive abrasion or total failure of large sections of revetment have occurred. Failure also may occur because of uplift from hydrostatic pressure after a rapid drawdown. Although permeability of the asphalt increases with age, the pores of the pavement rapidly become clogged with silt, which increases the possibility of failure due to buildup of hydrostatic pressure. A subsurface drainage system can eliminate this problem in some cases.

63. Annual surveys have shown that the wearing rate of asphalt paving on upper banks is 1/16 to 1/8 in. per year as a result of abrasion. A very thin surface layer of the asphalt weathers until it loses its adhesive qualities. This can be observed on most asphalt revetments, as the mix takes on a light brown appearance and loses its cohesiveness in the thin layer. In this condition, the thin layer is easily removed by rain, wind, and water currents, and then the weathering process is repeated. If it is assumed that the yearly rate of surface wear is a maximum of about 1/8 in., at the end of 25 years the bank slope will be covered with a 2-in.-thick pavement, which is considered to be serviceable in some situations. This may be a reasonably good minimum estimate for the design life of asphalt pavements on upper bank revetments based on natural deterioration and wear. It should also be noted that the asphalt binder deteriorates with age and the pavement becomes more brittle. Hence, the pavement becomes more subject to massive mechanical failures due to floodwater velocities, impact by debris, hydrostatic pressure, or penetration by vegetation.

64. In-place average cost (1976) for asphalt used for upper bank paving is \$60 to \$80/yd^3 including the costs for bank preparation (Table 5).

65. Between 1946 and 1949 trial installations of subaqueous protection composed of mass asphalt mix at temperatures of 225-275°F were placed along the banks of the lower Mississippi River. Loads of 330 tons of hot mix containing 25 percent asphalt were dumped in bulk by hopper barges covering a slope surface of 600 yd^2 extending out 300 ft from the toe of the bank. The experiments demonstrated that a sand-asphalt mixture can be dropped in a large mass through a considerable depth of water and develop a satisfactory mat. This method, although successful, has been largely neglected except for patchwork, because the major emphasis has been placed on development of articulated concrete mattresses.

Kellner Jack Field

66. The term "jacks" includes a variety of wooden, metal, and concrete configurations. The most common consists of three linear members that are bolted or welded at their midpoint such that each member is perpendicular to the other two (similar to the shape of a toy jack). The members are laced together with cable. The jacks are then assembled in a linear array and connected at intervals of 15-30 ft with cables. Arrays that are parallel to streamflow are called diversion lines; those that make an angle with the flow are termed retard lines. The retard lines are attached to the bank with deadmen and extended into the channel where the free end is anchored to a diversion line. The resulting system is called a Kellner jack field (Figure 40).

67. Use of a Kellner field is considered to be an indirect bank protection method because the protection works are not in direct contact with the bank. The field is also considered to be a river "training aid," since the thalweg is moved away from the bank by the field. This displacement tends to scour out the main channel and improve navigation.

68. A Kellner field is permeable and extremely flexible and

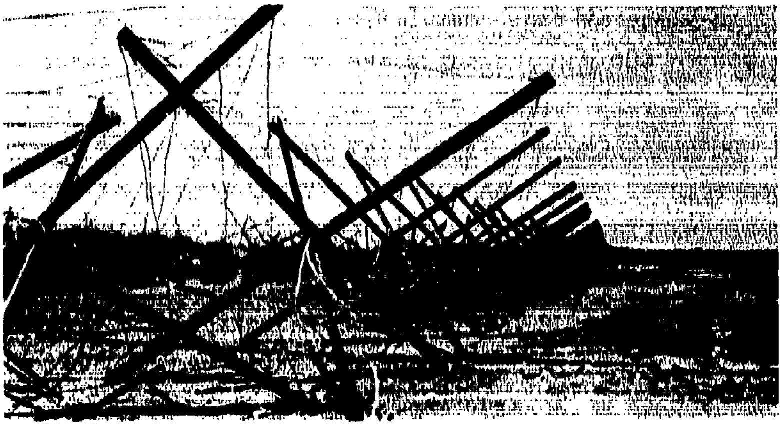


Figure 40. Kellner jack field

readily conforms to channel geometry. The placement of Kellner fields has found wide application in the southwestern and midwestern United States where the wide, shallow, silt-laden streams are subject to severe scour during high-velocity flows. The flow velocity may be reduced from a peak of 5 fps to 0.50 to 0.25 fps by an effective Kellner field. The jacks and connecting cable slow the current and cause deposition of the suspended sediments, which in turn build up eroded banks. This system also encourages the collection of debris, which improves the effective density of the works and removes dangerous obstacles from the navigation channel. Vegetation, which not only provides additional bank protection, but also reduces the channel area exposed to evaporation, usually becomes rapidly established in the built-up areas behind the retard lines. This promotes water conservation, an important consideration in arid and semiarid regions.

69. The Kellner field was developed in the 1920's as an economical alternative to pile dikes. Since then, this system has been used for a variety of long-term and emergency protection measures. The jacks can be constructed from used angle iron or rails and can be assembled by inexperienced crews in a relatively short time. The Santa Fe Railroad initially used the system on a large scale in Kansas, Oklahoma, Texas, and New Mexico. Some of the fields have been in place over 25 years. The only maintenance has been the replacing of sections of arrays that

were damaged by debris. Some corrosion has been noted on the jack members, but the useful life of a field should be in excess of 50 years. Successful use of Kellner fields also has been reported by the Albuquerque, Sacramento, and San Francisco Districts of the U. S. Army Corps of Engineers and by the Texas, Oklahoma, and Kansas highway departments.

70. Average initial cost of the field is a function of the availability of used materials. The cost (1976) varies from $16/ to $47/lin ft, which includes the costs of the jacks, the cable to connect them, deadmen on the bank, and labor (Table 5).

71. Although Kellner fields are not aesthetically harmonious with a floodplain landscape, they have proven to be effective when used in locations where timber and riprap are not economically available, but scrap materials are. Jacks are not recommended for use in areas with a corrosive atmosphere, where extremely high velocity flows are experienced, or where the banks to be protected are higher than the jacks.

Vegetation

72. The principal functions of vegetation for streambank protection are to keep fast-moving water and transported coarse materials away from the surface of a streambank slope and to improve the structural integrity of the bank. Vegetation is generally divided into two broad categories: grasses and woody plants. The grasses require much less time than the woody plants to become established on banks, but offer less protection during periods of high-velocity flow (Figure 41). Experiments[19] have demonstrated that the ability of grass to reduce stream velocity (and hence retard erosion) is directly related to the length, width, and density of the blade, the areal density of the grass, and the depth of the root system. A well-established stand of selected grass can reduce the stream velocity as much as 90 percent at the boundary layer between the water and the soil.

73. The major factor affecting the selection of a particular species of grass to be planted is the length of time required for the grass stand to become established on the slope. The selection of a

Figure 41. Grass used for bank protection

grass species is also based on soil and air temperature, total rainfall and distribution of rainfall, type of soil available for planting, the slope of the bank, and the ability of the soil to store water for plant growth during dry periods. Some species having physical attributes that provide optimum resistance to erosion often must be excluded from use in regions where the growing season is short or where the banks are subjected to prolonged periods of submergence.[20]

74. The topsoil of the bank to be protected is generally stripped because it provides a fertile bed that enhances weed growth, which tends to choke out the grass. The soil that is exposed is usually rolled and then scarified prior to planting. The grass can be planted by sodding, sprigging, or more commonly by the mechanical broadcasting of mulches consisting of seed, fertilizer, and other organic mixtures (Figure 42).

75. Woody plants generally have a greater initial cost than grass and require a longer time to become established, but they provide more effective long-term protection. For sections of a streambank where scour is a problem, woody plants established at the toe of the

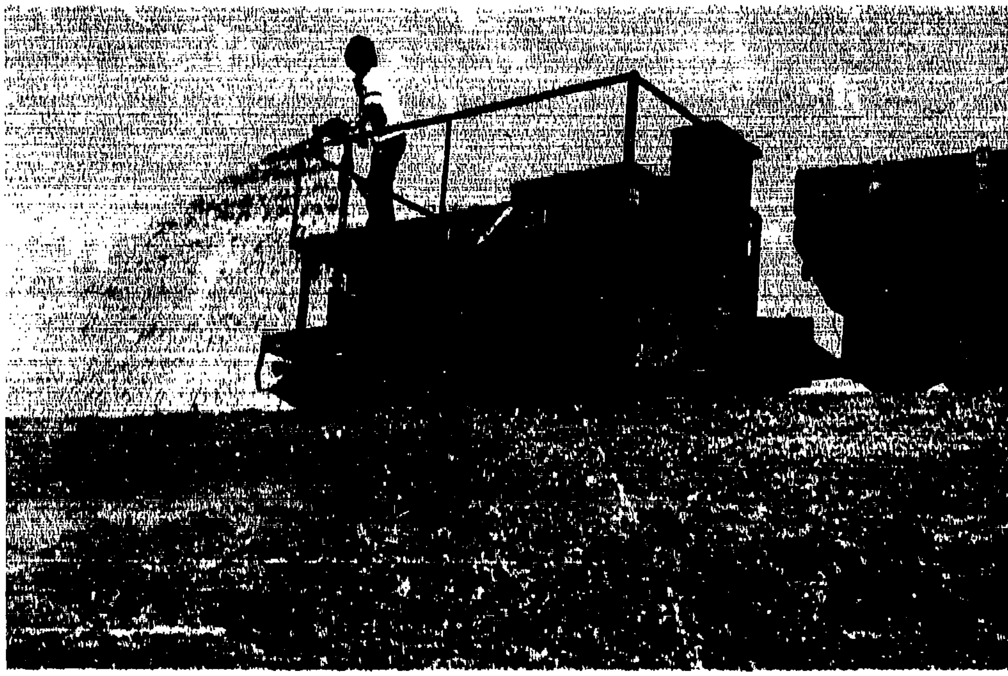


Figure 42. Mechanical broadcaster spreading mulch on stream top bank (photo courtesy of Bowie Industries)

slope and grass above the toe have proven to be good protection. Trees raised in nurseries are preferred over local plants because they are usually healthier, bushier, and have better developed root systems at maturity.

76. Above the mean high-water line of bank slopes and in backwater areas, the major soil erosive action results from the mechanical disintegration of soil masses by alternate wetting and drying (periods of precipitation and sunshine) and wind. Grasses have proven to be excellent deterrents to soil erosion under these conditions. Of all the bank protection methods, vegetation is the only self-renewable method and in many cases the most economical and aesthetically pleasing.

77. The cost (1976) of planting grass ranges from $500 to $650 per acre, including soil preparation and fertilizer (Table 5). If woody vegetation is planted with the grass, the average cost is approximately three times that of grass alone.

Gabions

78. Prefabricated gabion cages have been marketed in Europe for many years; however, gabions for the construction of bank protection works in the United States have been used widely only in the past 15 years. The basic element of the gabion works is the cage or "basket." The cage is a rectangular wire-mesh structure divided by diaphragms into cells (Figure 43). The mesh is generally galvanized steel wire, which

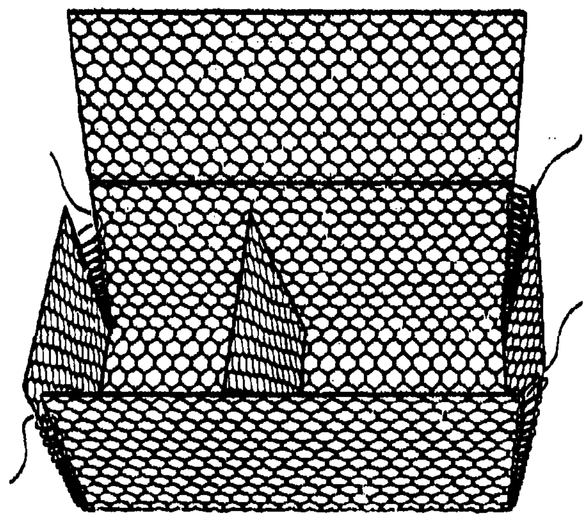


Figure 43. Gabion cage (photo courtesy of Maccaferri Gabions, Inc.)

is coated if the gabions are to be used in a corrosive atmosphere.

79. Prior to placement of the cages, a support apron is laid on the bank that will extend at least 6 ft past the toe of the gabion works (Figure 44). The apron, also constructed of gabion cages, has a minimum height 1.5 to 2 times the depth of the scour predicted at the toe of the bank. Each cage is placed and securely wired to the apron or its neighbors and then filled with stone. Ideally, the stone should be slightly larger than the wire mesh and should be of maximum available density. It should also be able to physically withstand abrasion and be nonfriable and resistant to weathering and freeze-thaw actions. To avoid bulging at the sides of the cage, tie wires are often connected between opposite

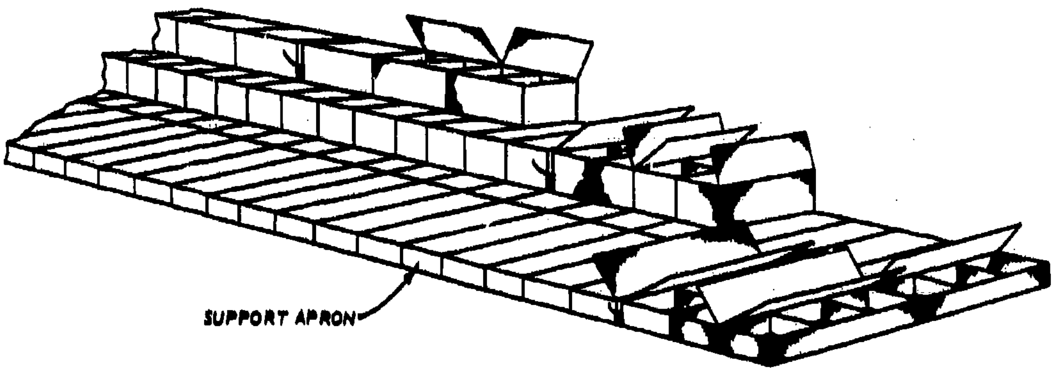


Figure 44. Typical arrangement of gabions used to protect a streambank (photo courtesy of Maccaferri Gabions, Inc.)

walls inside the cells prior to filling with stone.

80. Gabion works are somewhat flexible and are therefore able to accommodate minor changes in bank geometry. The voids between the stones allow bank drainage, which aids in the elimination of failures due to excessive hydrostatic pressure. Filter cloths are sometimes used behind gabions to prevent excessive soil losses.

81. Current in-place costs (1976) for gabion works (Figure 45) are \$40/ to \$47/yd^3 (Table 5). The costs can be reduced somewhat for very large projects near economical sources of stone.

Erosion-Control Matting

82. A variety of erosion-control mats are available on the commercial market. Many of these mats are produced from by-products of other manufacturing processes. This type of bank protection is generally installed by hand (Figure 46) and secured to the bank with stakes or staples. For some applications, the matting, stakes, and staples are biodegradable.

83. The matting is structured in the form of a web, which allows vegetation to grow through the mat. In many design applications, this is considered to be a short-term bank protection measure that allows natural vegetation to reestablish itself on an eroding bank or allows

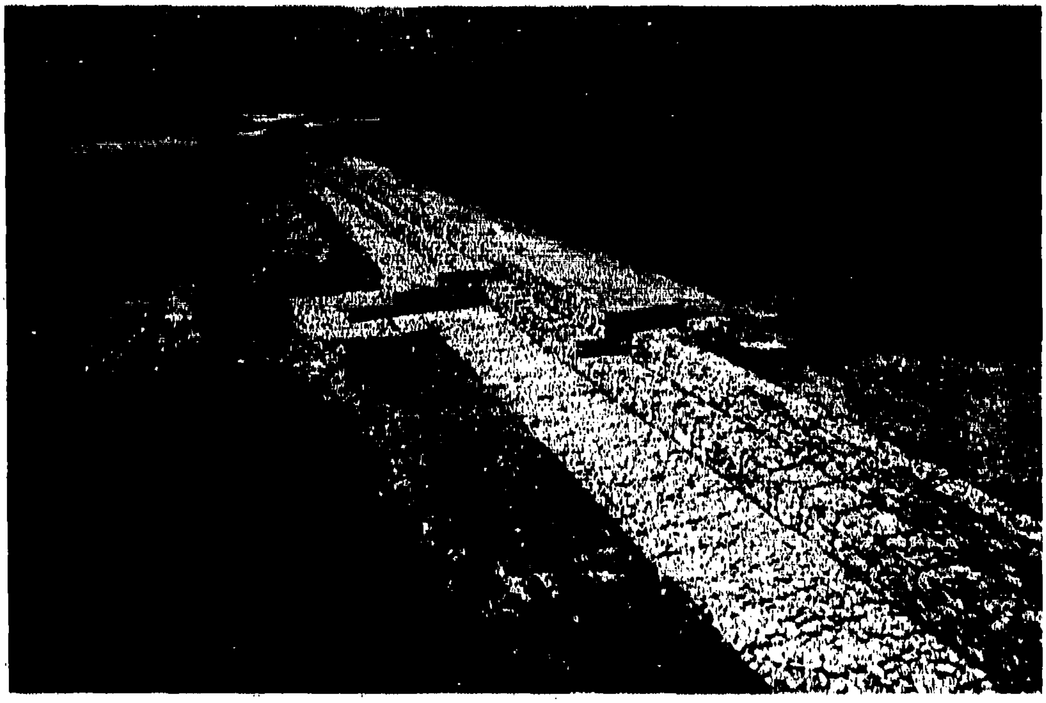


Figure 45. In-place gabion works (photo courtesy of Maccaferri Gabions, Inc.)

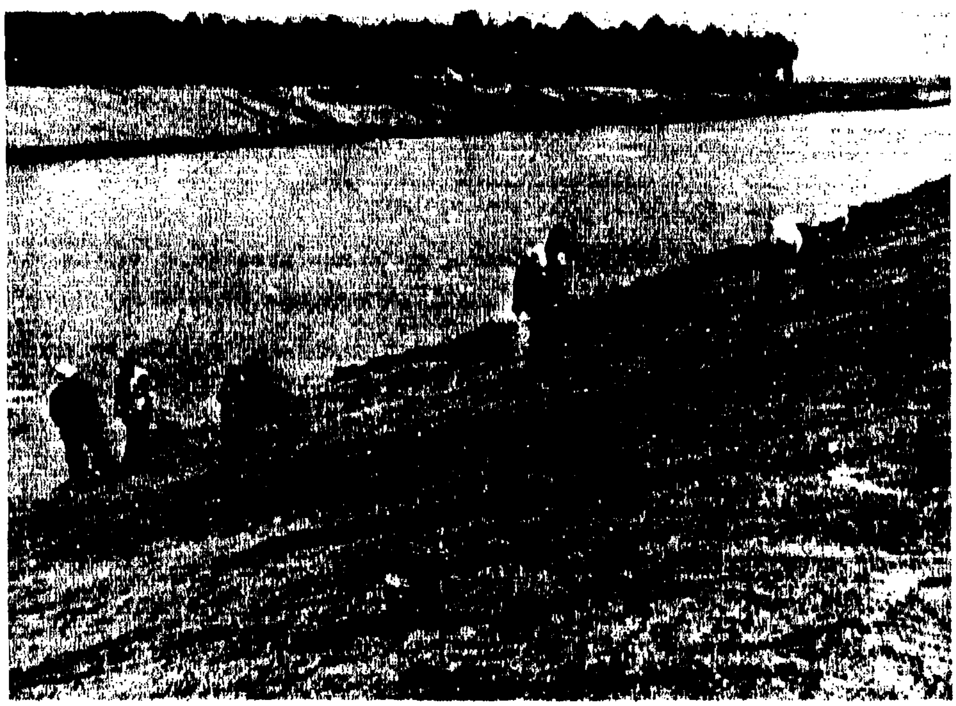


Figure 46. Erosion-control matting being placed by hand

new vegetation adequate time to become established. Some of the currently available mats decompose and add organic matter to the topsoil. Nonorganic webbing has caused some problems during later grass cuttings because of its tendency to become tangled with mower blades.

84. Installed costs (1976) for matting ranges from \$0.50/ to \$0.65/yd^2 (Table 5).

Bulkheads

85. Bulkheads are used to protect streambanks when the bank slope is unstable, to expedite the flow of traffic across the water-land interface, or when additional waterfront area is required, i.e. filling behind the bulkhead. A timber bulkhead (Figure 47) generally costs less initially than a comparable concrete bulkhead, but its design life is shorter because of deterioration and destruction caused by repetitive cycles of wetting and drying and attack by organisms. A concrete bulkhead (Figure 48) can provide long service if failures due to cracking or pressure from the fill behind it can be avoided.[6,74] Concrete bulkheads generally require minimal maintenance; whereas timber requires regular application of wood preservative to minimize deterioration.[75-77] Hence, costs (initial plus long term) are in many cases nearly the same.

86. Prefabricated asbestos fiber (Figure 49) and metal (Figure 50) bulkheads are available from commercial sources. Each sheet of commercial bulkhead is worked into the soil with a compressed air jet or is driven into the ground with a mechanical aid. The sheets are then joined together and capped. The use of sheet bulkheads eliminates the necessity for driving deep piles or, in some cases, constructing concrete forms; concrete caps are used on some projects.

87. Installed costs (1976) for bulkheads range widely from \$14/ to \$105/lin ft (Table 5), depending on availability of materials. Costs of concrete, timber, aluminum, and fiber bulkheads are generally competitive, at an average of \$50/lin ft when materials are readily available.

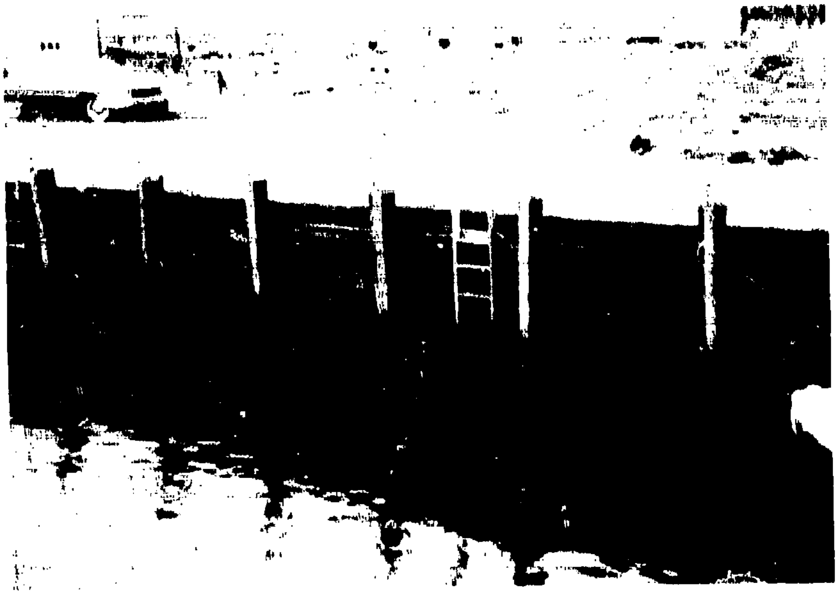


Figure 47. Timber bulkhead

Figure 48. Concrete bulkhead (photo courtesy of the Portland Cement Association)

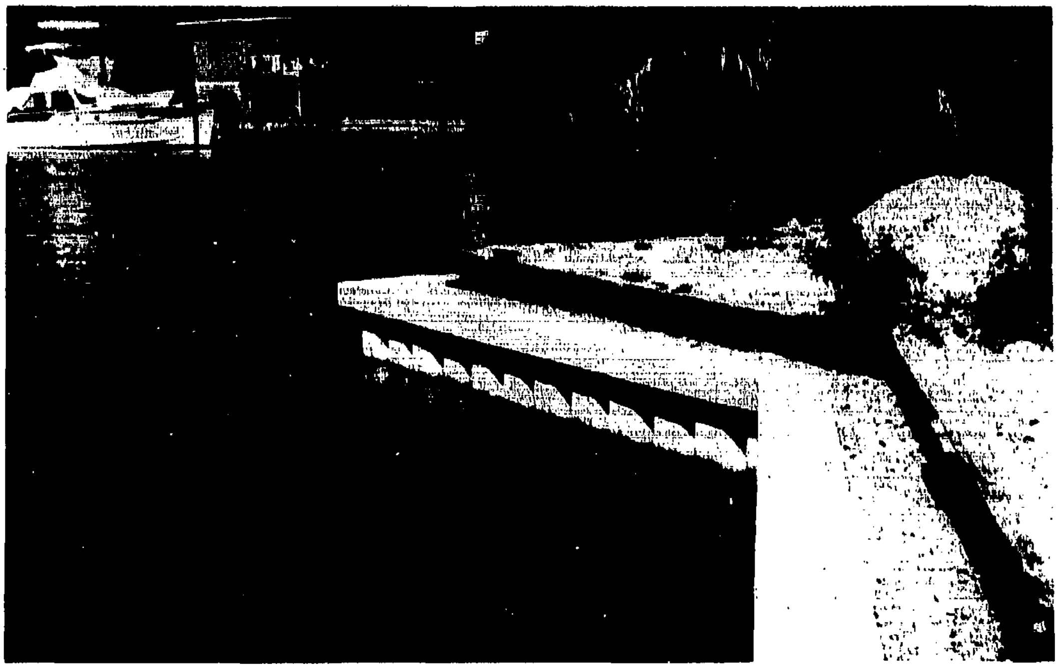
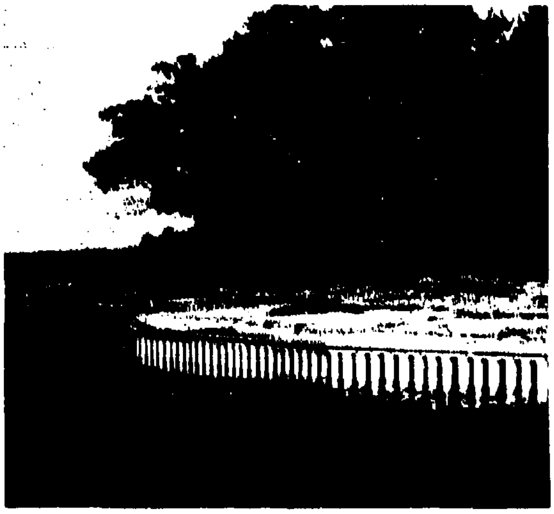


Figure 49. Asbestos fiber bulkhead (photo courtesy of GAF Corporation)

Figure 50. Aluminum bulkhead (photo courtesy of Kaiser Aluminum)



Other Methods for Streambank Protection

Limited-use methods

88. Additional methods for streambank protection have found application in the United States; however, these methods are not used as widely as those discussed in paragraphs 33-87 because of the lack of locally available materials or manufacturing processes. These limited-use methods are briefly discussed below. No costs are provided because the cost data that are available are generally applicable only to local areas.

89. Automobile bodies. Automobile bodies are used by farmers and other landowners as an emergency or low-budget bank protection method. The bodies are generally placed along the bank in random fashion (Figure 51) and laced with wire cable that is secured to deadmen

Figure 51. Automobile bodies on a streambank

or trees. Although the use of automobile bodies is assumed to be a preventive measure, bank erosion is sometimes actually increased by the bodies because their random placement and shapes may direct the flow towards the bank instead of away from it. Automobile bodies have been used mostly along small streams in areas where riprap is not economically available, where heavy ice flows are not a problem, and where the waters do not cause excessive rust. Large-scale use of automobile bodies as bank protection devices would improve the landscape aesthetically by eliminating some of the junkyards scattered along the nation's highways but would make the banks of streams unsightly and inaccessible.

90. Cellular blocks. Precast cellular blocks are available from several commercial sources (Appendix B). These blocks are cast with cells to allow vegetation to grow through the blocks thus permitting the vegetation root structure to enhance the structural integrity of the bank (Figure 52). Filter cloths are used under the blocks where

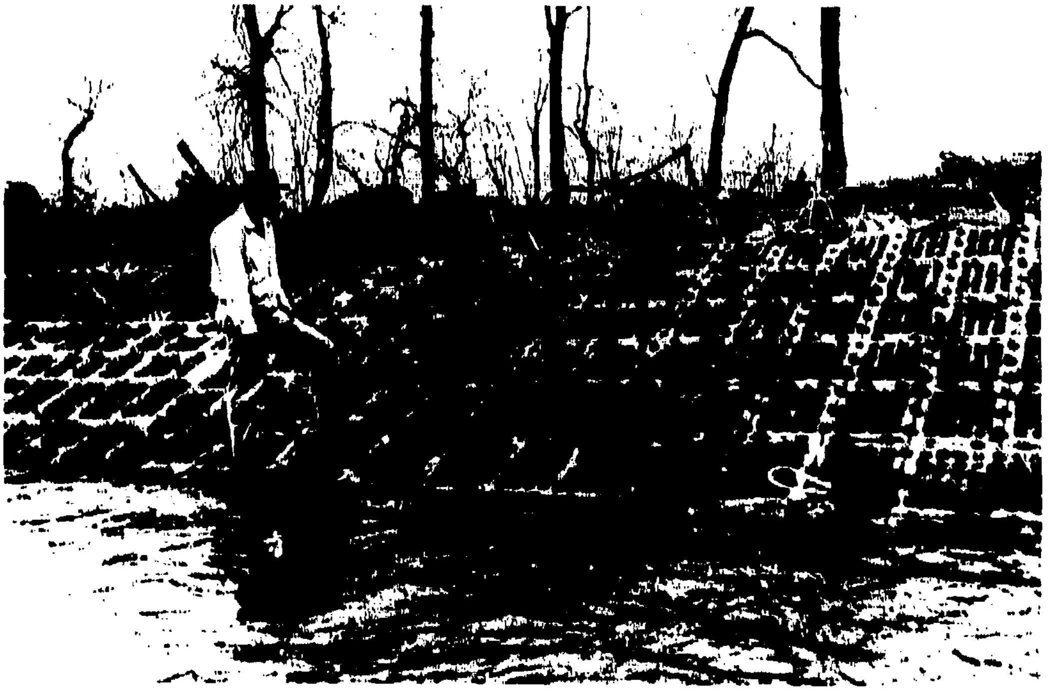


Figure 52. Cellular blocks (photo courtesy of D. A. Parsons, Agricultural Research Service, U. S. Department of Agriculture)

soil erosion is a problem. Although specialized equipment is available to install large sections of cellular blocks, hand placement is frequently used when mechanized apparatus is not available or access to the bank is not adequate. After the cellular blocks have been placed, the resulting revetment has sufficient flexibility to conform to minor changes in bank geometry. In areas of the United States where riprap is not readily available, cellular blocks can provide a viable substitute.

91. <u>Ceramic materials.</u> Ceramic riprap and ceramic mattresses have had very limited application as bank protection. The only known ceramic riprap revetment in the United States, which is now underwater, was placed on the Ohio River by the Corps of Engineers above the present location of Markland Dam. The majority of information available on the use of ceramics for bank protection can be found in Reference 24.

92. <u>Concrete blocks.</u> Precast concrete blocks as well as recycled block (sidewalks, roadways, etc.) have application in areas where suitable stone is not available for riprap revetment or where a source of salvaged blocks is readily available. Costs for a revetment of precast blocks (Figure 53) generally are higher than for a comparable revetment of riprap because of the casting process and individual placement of the blocks. More salvaged blocks could be used in future bank protection works as more highway reconstruction projects are implemented (Figure 54).

93. <u>Rock-and-wire mattresses.</u> This type of bank protection consists of riprap encased in wire (Figure 55). With the use of the wire, the depth of the revetment can be less than for a comparable riprap blanket, and the wire retards loss of individual stones. Although less stone is needed, the cost is more than that of a riprap blanket because of the labor required to fabricate the wire casing.

94. <u>Rubble.</u> Widespread urban renewal projects and other redevelopment efforts have made large quantities of rubble available. Although somewhat unsightly (Figure 56), rubble can provide excellent bank protection for projects where minimal funds are available, such as those frequently planned by private landowners.

95. <u>Sack revetment.</u> Sacks made of burlap and filled with soil, soil-cement, sand, or sand-cement mixtures have long been used for erosion protection around hydraulic structures and for emergency work along levees and streambanks during floods. The burlap bags eventually

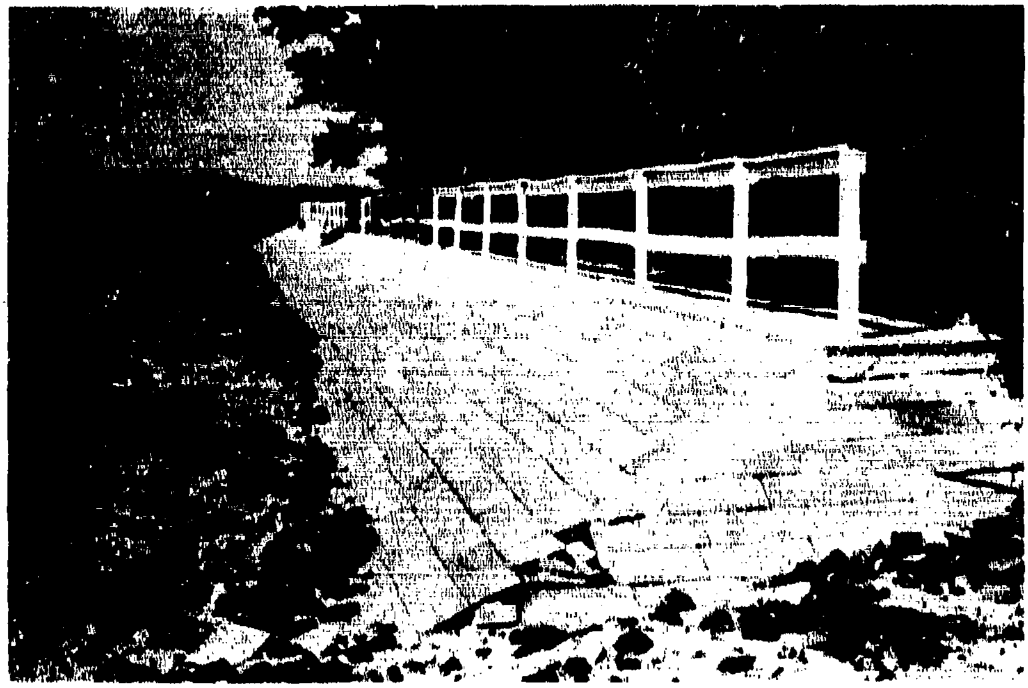


Figure 53. Precast concrete blocks (photo courtesy of Portland Cement Association)

Figure 54. Concrete blocks salvaged from highway reconstruction project

Figure 55. Rock-and-wire mattress

Figure 56. Rubble used for bank protection

rot; therefore, only bags filled with soil-cement or sand-cement mixtures provide long-term benefits. On-site mixing of cement and sand obtained from the streambed and placed on the bank in biodegradable sacks now being marketed can provide an effective alternative (Figure 57) to the

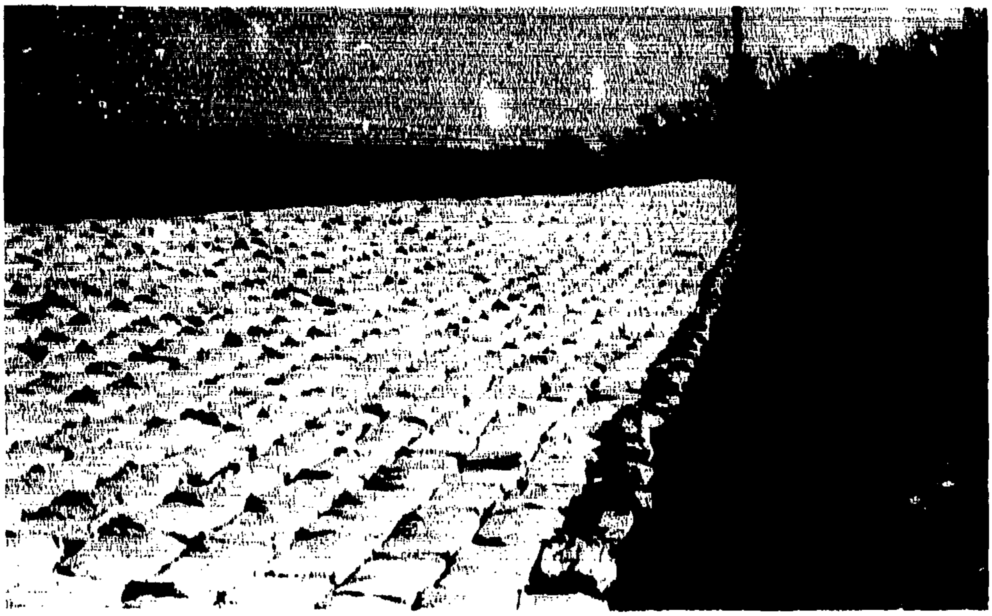


Figure 57. Sack revetment using biodegradable material for the sacks

use of riprap in areas where suitable stone is not available.

96. Soil cement. Soil-cement pavement and blocks have found wide application in the protection of upper banks and, to a lesser extent, in lower banks. Soil-cement pavement (Figure 58) containing 8 to 15 percent portland cement has the advantages of ease of placement, low cost, and availability of materials; however, lack of flexibility and low permeability precludes its use for applications where changes in bank geometry must be accommodated by the revetment, when traffic must be sustained, or when the bank must be drained to maintain stability. Soil-cement blocks have been used in Asia for many years as a substitute for riprap; however, blocks have been used at only a few sites in the United States. Adequate engineering data to determine their effectiveness are not yet available.

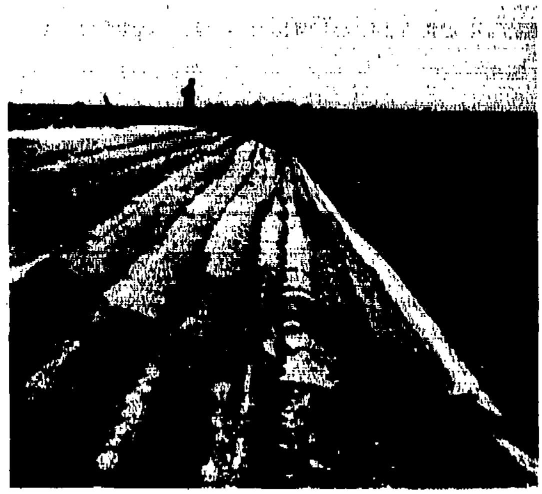


Figure 58. Soil-cement mixture used to pave bank (photo courtesy of Portland Cement Association)

97. Synthetic mattresses, matting, and tubing. Several manufacturers are marketing synthetic casings (Appendix B) that are filled in place or on the bank to be protected with locally available sand (Figure 59) or other materials. Many of these products have been used as foreshore protection (especially in Europe) and are now being used as

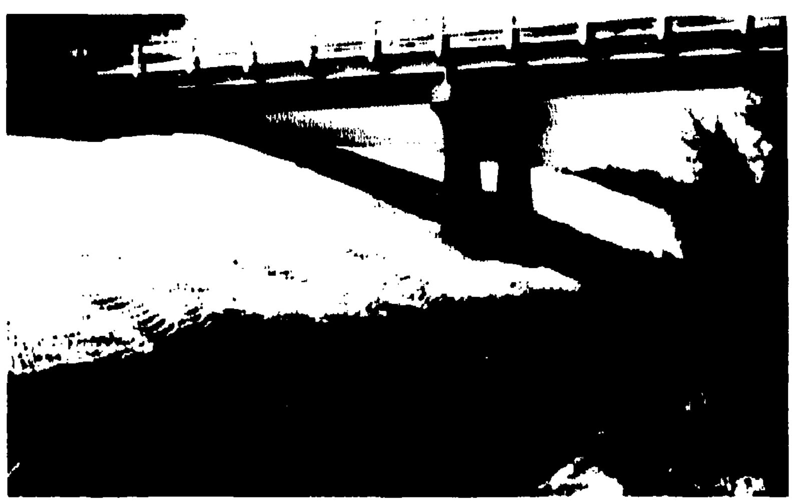


Figure 59. Synthetic casing used to protect a streambank at bridgehead (photo courtesy of Construction Techniques, Inc.)

direct bank protection in areas where sand is available.

98. Temperature control. Limited experiments have been conducted to determine the feasibility of using freezing and fusion processes to stabilize in situ soils on streambanks. In polar climates, steel probes have been used to prevent thawing of frozen banks during summer months (Figure 60). Installation and operation of freeze probes are expensive; hence, the only known installations are in polar locations where stone is not available and property or structures must be protected.

99. Soils can be stabilized to increase their strength and resistance to erosion by heat fusion. Because of increasing costs for fuels, this process may have limited potential; however, experiments have been reported for this method.[24]

100. Tetrapods. Tetrapods have been used effectively for many years as foreshore protection to dissipate energy resulting from continuous wave action. Some use is now being made of tetrapods as components of bank protection revetment (Figure 61). The geometric configuration and mass of tetrapods affords excellent stability under the action of hydraulic forces; however, a casting facility is needed for fabrication and heavy equipment for placement; therefore, tetrapods have not been widely used on streambanks.

101. Used-tire matting. Mattresses constructed of used automobile tires have been successfully employed as streambank protection by the U. S. Army Engineer District, Sacramento; U. S. Bureau of Indian Affairs, Oklahoma; Washington State Highway Department; West Virginia Department of Natural Resources, and U. S. Forest Service, Mississippi. The used tires are generally put in place as a mat (Figure 62). They are laid over the surface to be protected and lashed together with wire or nonbiodegradable rope to form a mat structure. The mat is held in place on the slope by deadmen anchors to prevent it from sliding down the bank or floating. Holes are sometimes drilled in the sidewalls of the tires to allow trapped air to escape and prevent mat flotation. After vegetation becomes established and sediment builds up, mat stability becomes less of a problem.

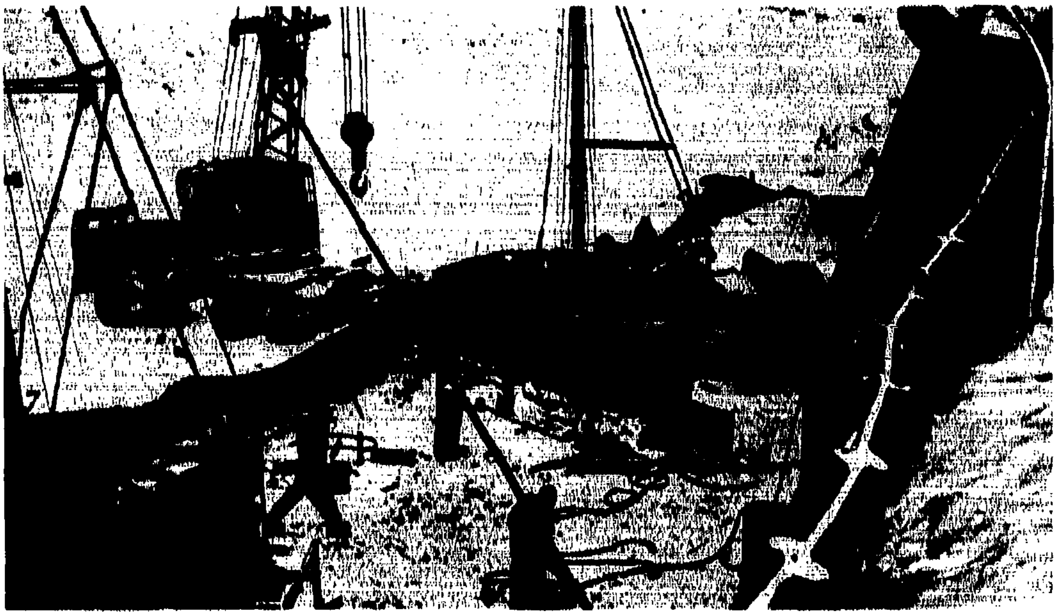


Figure 60. Freeze probe being inserted into streambank (photo courtesy of Western Construction)

Figure 61. Tetrapods (photo courtesy of California Department of Transportation)

Figure 62. Automobile tires on a streambank

Obsolete methods

102. Several methods for streambank protection that were employed earlier are now no longer widely used because of increased labor costs, lack of materials, or the development of more effective streambank protection techniques. These methods which are generally regarded as being obsolete include fascine mattresses, timber and brush, log and cable, cribs, and tetrahedrons.

103. Fascine mattresses. A fascine mattress consists of bundles of untreated tree stems roped together and placed on the bank to be protected (Figure 63). This technique was used on the lower Mississippi River during the early part of this century when there was an abundant supply of willow trees along the banks as a source of timber.

104. Timber-and-brush mattresses. Timber-and-brush mattresses were used extensively for upper and lower bank protection in the latter portion of the nineteenth and early part of the twentieth centuries. Timber and brush were woven by hand into a mattress that was launched from a barge (Figure 64). After the mattress was secured to the bank, stone ballast was placed on the mattress to sink the mattress onto the

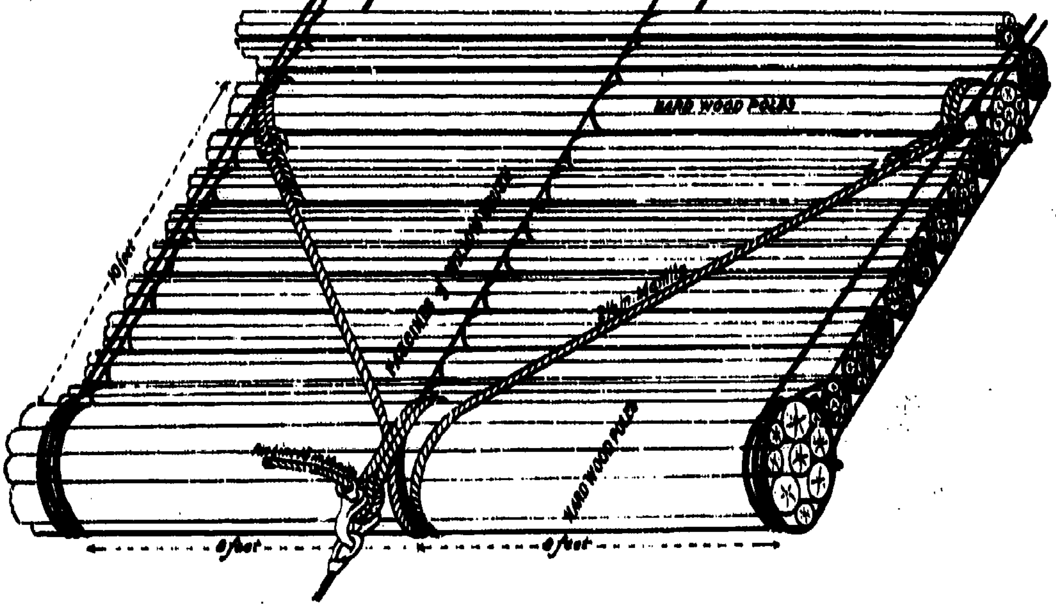


Figure 63. Fascine mattress

Figure 64. Assembly of timber-and-brush mattress on launch barge

portion of the bank below the waterline and to improve the upper bank stability under hydraulic loading (Figure 65). Fascine mattresses as

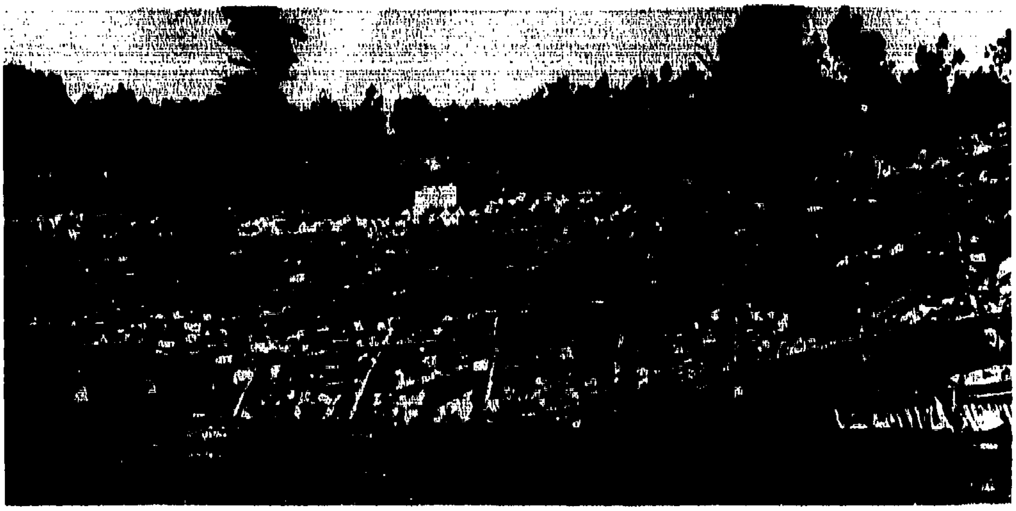


Figure 65. Timber-and-brush mattress with stone ballast

well as timber and brush mattresses have limited design lives as upper bank protection due to timber rot. The alternate wetting and drying of the timber by rain and stage change tend to cause the effectiveness of the mattress to rapidly decrease as the timber rots. Because of the limited design life of the mattresses as upper bank protection, the depletion of sources of timber near the Mississippi River, and the inordinate amount of hand labor involved, use of these mattresses was abandoned by the Corps of Engineers in favor of bituminous and articulated concrete mattresses (bituminous mattresses have not been used since 1945, paragraph 60).

105. Log and cable, and cribs. Streambanks have also been protected directly with timber cabled to deadmen (Figure 66) and earth- or stone-filled cribs made of timber (Figure 67) that direct erosive currents away from the streambank. These methods have been used primarily on small streams and are now being used on a very limited basis in the western United States.

106. Tetrahedrons. Tetrahedrons (Figure 68) are used to construct permeable dike fields that are arranged in a manner similar to a

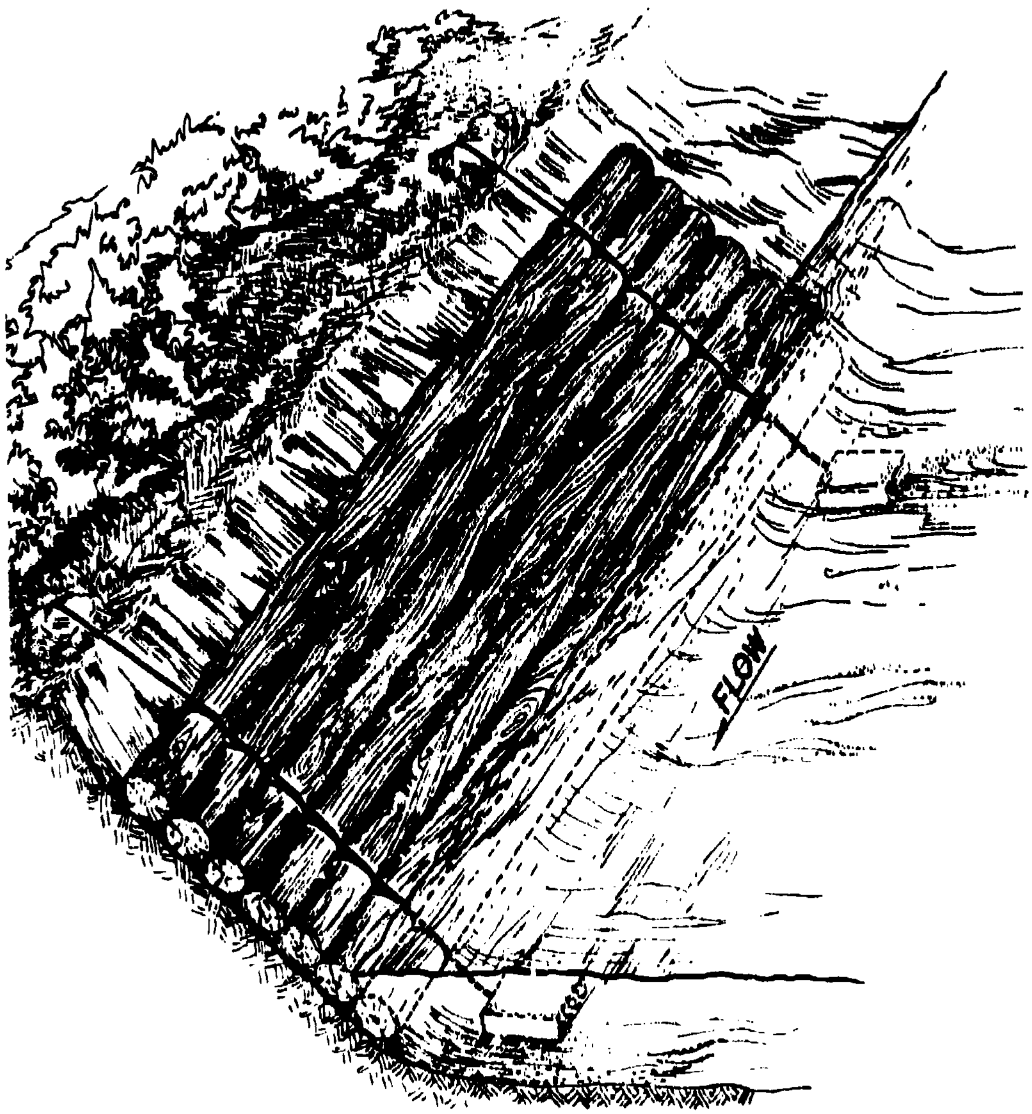


Figure 66. Log-and-cable revetment

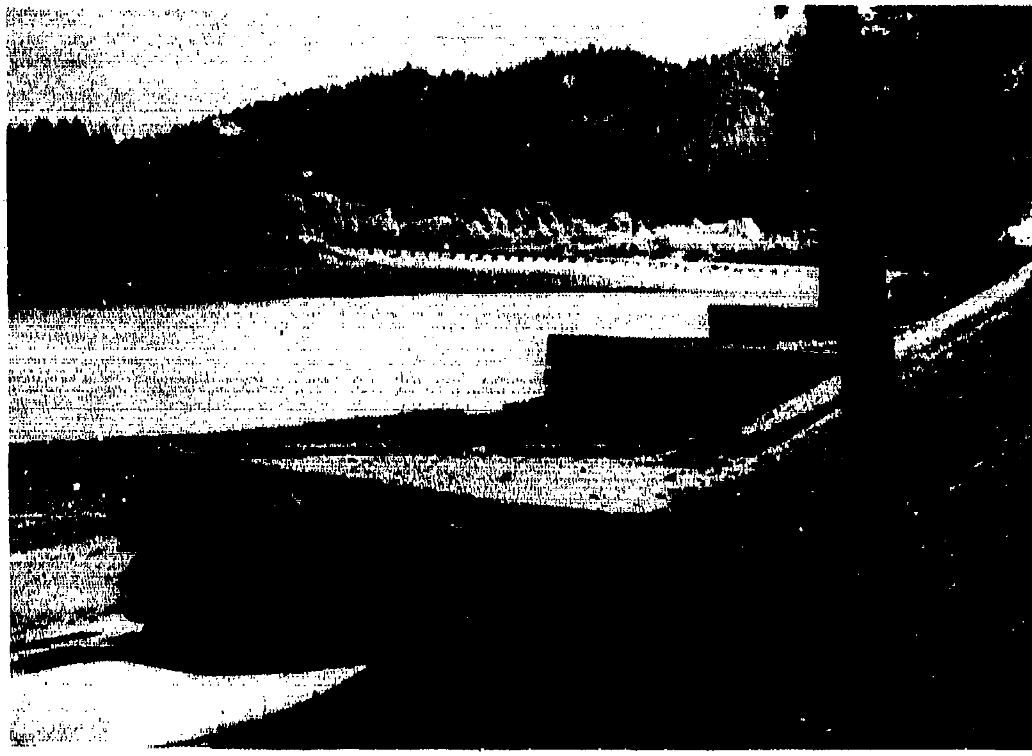


Figure 67. Cribs (photo courtesy of California Department of Transportation)

Figure 68. Tetrahedrons (photo courtesy of California Department of Transportation)

Kellner jack field (paragraphs 66-71). Six sections of rail or beam are required to fabricate a tetrahedron but only three for a comparable jack; hence, tetrahedrons have not been used as much as Kellner jacks even though the tetrahedrons are more stable under hydraulic loading.

PART V: NEW METHODS OF STREAMBANK PROTECTION

107. One of the major objectives of the Streambank Erosion Control Evaluation and Demonstration Act of 1974 (Appendix A) is the development of new methods for effective and economical bank protection. Many innovative methods are currently being discussed and field-evaluated on a limited basis.[78-87] The following methods are among the most promising for upper bank protection:

- a. Used-tire mattress of interconnected tubes positioned perpendicular to the stream (modular units composed of tires stacked on edge, filled with sand and gravel, and interconnected with a steel cable through concrete-filled tires placed on either end of the sand- and gravel-filled tires to complete the modular unit).
- b. Membrane encapsulated soil systems (continuous bank paving and soil-filled bag revetment).
- c. Chemical stabilization (portland cement, lime, or asphalt) to form monolithic stabilization, stabilized soil blocks, stabilized soil trenches parallel to the stream, chemically grouted soil piles, and continuous armor coating.
- d. Rigid or collapsible honeycomb material backfilled with soil.
- e. Reinforced earth systems employing membranes and fabrics.
- f. Local waste products (without treatment, with minor processing, chemically treated, or membrane encapsulated).
- g. Military surplus products such as lightweight pierced landing mat, antisubmarine net, and floating bridges.

108. The following methods should be considered for improved lower bank protection:

- a. Used-tire gabion-like bulkhead (modular units with tires stacked vertically, filled with sand and gravel, and interconnected with a steel cable through concrete-filled tires placed on either end of the sand- and gravel-filled tires to complete the modular unit).
- b. Used-tire mattresses (paragraphs 101 and 107a).
- c. Reinforced earth systems employing membranes and fabrics (paragraph 107e).

d. Stabilization of large masses of soil to form an "artificial clay plug" of controlled dimensions.

e. Root piles (soil stabilization technique consisting of an array of slender piles driven into the streambank; Appendix B).

PART VI: CONCLUSIONS AND RECOMMENDATIONS

Conclusions

109. This report, including the references on erosion and the selected bibliography on streambank protection methods presented in Appendix D, should provide sufficient information to establish the current state of the art on both streambank erosion and the commonly used streambank protection methods.

110. The various types of streambank erosion have been well documented. Existing methods of studying streambank stability include movable-bed hydraulic models and empirical relations based on physical characteristics of stable channels only.

111. The erosion of soils is a function of many parameters, some of which have been identified only recently. There is no available general solution relating all of these parameters to the relative resistivity of soils to erosion. Within the present state of the art, a quantitative procedure for evaluation of streambank stability would require determination of the erosion rate versus hydraulic shear stress from laboratory tests on undisturbed soil samples.

112. The state of the art of streambank protection has not advanced significantly since 1950[88] (except for a few patented techniques that have been used on a very limited basis); therefore, the selected bibliography in Appendix D should remain current with only minor revisions as new work is documented.

113. Streambank erosion and hydraulic conditions vary so widely from one location to another that it has been considered good engineering practice to solve each bank protection problem independently. Under similar erosive and hydraulic conditions (whether natural or man-made), no method has universal applicability because of logistic and economic constraints such as the availability and cost of materials, transportation, construction equipment, and manpower. An urgent need exists to develop general design guidelines for all effective streambank protection methods, including approaches that consider the entire stream basin

rather than protection of local reaches only.

114. Preliminary assessment of the effectiveness of the most commonly used streambank protection methods is presented in this report; however, further research and testing are required for complete evaluation. Initial examination of some of the less common methods for protecting streambanks indicates that worthwhile assessments will be difficult. Conversations with persons knowledgeable on the subject of streambank protection and examination of the available literature confirmed that much of the experimental bank protection design, especially that of private citizens and nongovernmental agencies, is not documented.

115. Streambank protection, in its present form, is, at best, "subjective engineering." Of all the methods surveyed, only one, stone riprap, has been studied in detail. The results from this research have not been collated for transfer to the practicing engineer in the form of general design criteria. Engineer manuals (References 71-73) can provide limited design guidance.

116. The program authorized by the Streambank Erosion Control Evaluation and Demonstration Act of 1974 will greatly assist in the needed research on streambank erosion and demonstration of effective protection methods.

Recommendations

117. On the basis of the information presented in this report, it is recommended that:

- a. A procedure be developed for evaluating streambank stability based on laboratory measurements of erosion rates and strength properties of undisturbed soils, considering both normal water levels and rapid drawdown.
- b. Research be conducted to define the causes and mechanisms of streambank erosion in terms of fluvial geology and to develop techniques for monitoring sedimentological conditions in stream channels.
- c. Both laboratory and field hydraulic research be conducted to develop and evaluate new methods and techniques for general application in protecting streambanks against erosion.

d. Practical design criteria be developed for determining the optimum riprap requirements on streambanks for straight and curved reaches because of its extensive and varied usage.

e. General limits of stream attack in channel bends be determined to minimize the length of streambank protection.

f. More effective and economical methods of streambank protection be validated by prototype field demonstration projects throughout the United States as directed by the Section 32 Program (Appendix A).

g. Those streambanks be identified that are too erosive or costly to protect.

h. Those streambanks be identified that require regulated floodplain use to prevent domestic or industrial bankline development. Floodplain regulation could permit low investment activities (tree farms, wildlife reserves, or recreational areas) and enhancement of the local environment.

i. Those streambanks be identified that merit no protection due to their slow rate of erosion.

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Table 1

Causes of Erosion and Bank Protection Methods Used for Selected Stream Classifications

Maximum Flow Rate, cfs	General Stream Classification and Examples	Causes Of Erosion*	Typical Bank Protection Methods Used
>1,000,000	Major alluvial (Mississippi)	1,3,4,5,6	1. Articulated concrete mattress 2. Stone riprap 3. Vegetation (upper bank & levees) 4. Monolithic concrete paving (levees) 5. Asphalt paving (upper bank) 6. Erosion-control matting (upper bank) 7. Bulkhead
≥500,000 to 1,000,000	Secondary alluvial (Missouri, Tennessee, Arkansas, Rio Grande)	1,3,5,6	1. Stone riprap or transverse dikes 2. Wooden piles or fences 3. Vegetation (upper banks & levees) 4. Jacks 5. Gabions 6. Erosion control matting (upper banks) 7. Bulkhead

(Continued)

* 1. Rainfall erosion of upper banks.
2. Overland flow (or runoff).
3. Current attack at toe of slope leading to shear in upper bank.
4. Flow slides (liquefaction).
5. Erosion of lower banks and channel by current action.
6. Erosion of banks and channel by wave action due to wind or passing boats.
7. Erosion of banks by seepage water at relatively low channel velocities.

Table 1 (Concluded)

Maximum Flow Rate, cfs	General Stream Classification and Examples	Causes of Erosion	Typical Bank Protection Methods Used
≥100,000 to 500,000	High-gradient tributary (Republican, Delaware, Allegheny, Black Warrior)	2,3,5,7	1. Stone riprap or transverse dikes 2. Wooden piles or fences 3. Vegetation (upper banks) 4. Gabions 5. Erosion-control matting (upper banks)
≥100,000 to 500,000	Low-gradient tributary (Red, Snake, Sacramento, Apalachicola, Illinois)	2,3,5,7	1. Stone riprap or transverse dikes 2. Wooden piles or fences 3. Jacks 4. Vegetation 5. Wire fences 6. Gabions 7. Erosion-control matting
<100,000	High-gradient tributary (Yellowstone, Nueches, French Broad, Kennebec)	2,3,5,7	1. Stone riprap or transverse dikes 2. Wooden piles or fences 3. Vegetation (upper banks) 4. Gabions 5. Erosion-control matting (upper banks)
<100,000	Low-gradient tributary (Ouachita, Oconee, Rock, Minnesota)	2,3,5,7	1. Stone riprap or transverse dikes 2. Wooden piles or fences 3. Jacks 4. Vegetation 5. Wire fences 6. Gabions 7. Erosion-control matting

Table 2

Streambank Protection Materials, Structures, or Methods

Single-Component Revetment

- Asphalt blocks
- Automobile bodies
- Cellular blocks
- Ceramic riprap
- Concrete blocks
- Rubble
- Sack revetment
- Stone riprap
- Tetrapods
- Trench-fill revetment

Mattresses, Matting, and Pavement Revetment

- Articulated concrete mattresses
- Asphalt pavement
- Bituminous mattresses
- Ceramic mattresses
- Concrete pavement
- Erosion-control matting
- Fascine mattresses
- Gabions
- Log and cable
- Rock-and-wire mattresses
- Synthetic mattresses, matting, and tubing

Mattresses, Matting, and Pavement Revetment (Continued)

- Timber-and-brush mattresses
- Used-tire matting

Bulkheads

- Concrete or stone
- Fiber
- Metal
- Timber

Soil Stabilization

- Asphalt (bulk)
- Grout
- Organic mixtures and mulches
- Soil cement
- Temperature control
- Vegetation

River Training Structures

- Cribs
- Dikes (sill, groin, spur, jetty)
- Fences
- Kellner jack field
- Tetrahedron field

Table 3

Classification of Alluvial River Channels for Rivers Transporting Less Than 20 Percent Coarse Gravel (Reference 35)

Mode of Sediment Transport	Channel Sediment (m), %	Proportion of Total Sediment Load		Channel Stability		
		Suspended Load, %	Bedload %	Stable (Graded Stream)	Depositing (Excess Load)	Eroding (Deficiency of Load)
Suspended load	30–100	85–100	0–15	Stable suspended-load channel. Width-depth ratio less than 7; sinuosity greater than 2.1; gradient relatively gentle	Depositing suspended load channel. Major deposition on banks causes narrowing of channel; streambed deposition minor	Eroding suspended-load channel. Streambed erosion predominant; channel widening minor
Mixed load	8–30	65–85	15–35	Stable mixed-load channel. Width-depth ratio greater than 7 less than 25; sinuosity less than 2.1 greater than 1.5; gradient moderate	Depositing mixed-load channel. Initial major deposition on banks followed by streambed deposition	Eroding mixed-load channel. Initial streambed erosion followed by channel widening
Bedload	0–8	30–65	35–70	Stable bedload channel. Width-depth ratio greater than 25; sinuosity less than 1.5; gradient relatively steep	Depositing bedload channel. Streambed deposition and island formation	Eroding bedload channel. Little streambed erosion; channel widening predominant

Table 4

Nonscour Velocities for Soils (Reference 48)

Kind of Soil	Grain Dimensions mm	Mean Depth of River 0.4 m	1.0 m	2.0 m	3.0 m and More
	Values of Nonscour Velocities for Noncohesive Soils, m/sec				
Silt with fine sand, vegetable soil	0.005–0.05	0.15–0.20	0.20–0.30	0.25–0.40	0.30–0.45
Fine sand with admixture of medium grains	0.05–0.25	0.20–0.35	0.30–0.45	0.40–0.55	0.45–0.60
Fine sand with loam; sand of medium grain size with admixture of coarser grains	0.25–1.00	0.35–0.50	0.45–0.60	0.55–0.70	0.60–0.75
Coarse sand with admixture of gravel; sand of medium grain size with loam	1.00–2.50	0.50–0.65	0.60–0.75	0.70–0.80	0.75–0.90
Fine gravel with admixture of medium grains	2.50–5.00	0.65–0.80	0.75–0.85	0.80–1.00	0.90–1.10
Coarse gravel with sand and fine gravel	5.00–10.0	0.80–0.90	0.85–1.05	1.00–1.15	1.10–1.30
Small pebbles with sand and gravel	10.0–15.0	0.90–1.10	1.05–1.20	1.15–1.35	1.30–1.50
Medium-size pebbles with sand and gravel	15.0–25.0	1.10–1.25	1.20–1.45	1.35–1.65	1.50–1.85
Coarse pebbles with admixture of gravel	25.0–40.0	1.25–1.50	1.45–1.85	1.65–2.10	1.85–2.30
Small pavers with pebbles and gravel	40.0–75.0	1.50–2.00	1.85–2.40	2.10–2.75	2.30–3.10
Small-size cobblestone	75.0–100	2.00–2.45	2.40–2.80	2.75–3.20	3.10–3.50
Medium-size cobblestone	100–150	2.45–3.00	2.80–3.35	3.20–3.75	3.50–4.10
Coarse cobblestone	150–200	3.00–3.50	3.35–3.80	3.75–4.30	4.10–4.65
Boulders	200	3.50–3.85	3.80–4.75	4.30–5.35	4.65–5.50

Values of Nonscour Velocities for Cohesive Soils, m/sec

Mean Depth of River, m

Kind of Soil	Poorly Compact Soils Volumetric Weight Up to 1.2 tons/m^3				Medium Compact Soils Volumetric Weight 1.20–1.66 tons/m^3				Compact Soils Volumetric Weight 1.66–2.04 tons/m^3				Very Compact Soils Volumetric Weight 2.04–2.14 tons/m^3			
	0.4	1.0	2.0	3.0	0.4	1.0	2.0	3.0	0.4	1.0	2.0	3.0	0.4	1.0	2.0	3.0
Sandy loams (heavy)	0.35	0.40	0.45	0.50	0.70	0.85	0.95	1.10	1.00	1.20	1.40	1.50	1.40	1.70	1.90	2.10
Sandy loams (light)	0.35	0.40	0.45	0.50	0.65	0.80	0.90	1.00	0.95	1.20	1.40	1.50	1.40	1.70	1.90	2.10
Loess soils in the conditions of finished settlement	—	—	—	—	0.60	0.70	0.80	0.85	0.80	1.00	1.20	1.30	1.10	1.30	1.50	1.70
Loamy sands	← According to tabulation above depending upon the sand fractions →															

Note: Volumetric weights refer to the dry soil.

Table 5

1976 In-Place Cost* Summary for the Streambank Protection Methods Discussed in Paragraphs 33-87

Streambank Protection Method	Cost/Unit, $	Unit
Stone riprap	3.50-30.00	yd^3
Concrete pavement	90-125	100 ft^2
Articulated concrete mattresses	84	100 ft^2
Transverse dikes:		
Pile board	40-55	lin ft
Untreated clumps	1500-2300	clump (three 60-ft piles)
Stone	40-65	lin ft
Fences	25-50**	lin ft
Asphalt mix (upper bank)	60-80	yd^3
Kellner jack field	16-47†	lin ft
Vegetation (grass)	1.15-1.49 (500-650)	100 ft^2 (acre)
Gabions	40-47	yd^3
Erosion-control matting	5.56-7.22 (0.50-0.65)	100 ft^2 (yd^2)
Bulkheads	14-105	lin ft

* Cost figures supplied by Corps of Engineers Divisions and Districts.
** Range applies to new materials.
† Range applies to used and new materials.

APPENDIX A: SECTION 32 OF THE WATER RESOURCES DEVELOPMENT ACT OF 1975, PUBLIC LAW 93-251 (STREAMBANK EROSION CONTROL EVALUATION AND DEMONSTRATION ACT OF 1974)

Section 32:

a. This section may be cited as the "Streambank Erosion Control Evaluation and Demonstration Act of 1974."

b. The Secretary of the Army, acting through the Chief of Engineers, is authorized and directed to establish and conduct for a period of five fiscal years a national streambank erosion prevention and control demonstration program. The program shall consist of:

(1) An evaluation of the extent of streambank erosion on navigable rivers and their tributaries;

(2) Development of new methods and techniques for bank protection, research on soil stability, and identification of the causes of erosion;

(3) A report to the Congress on the results of such studies and the recommendations of the Secretary of the Army on means for the prevention and correction of streambank erosion; and

(4) Demonstration project including bank protection works.

c. Demonstration projects authorized by this section shall be undertaken on streams selected to reflect a variety of geographical and environmental conditions, including streams with naturally occurring erosion problems and streams with erosion caused or increased by man-made structures or activities. At a minimum, demonstration projects shall be conducted at multiple sites on:

(1) The Ohio River;

(2) That reach of the Missouri River between Fort Randall, South Dakota, and Sioux City, Iowa;

(3) That reach of the Missouri River in North Dakota at or below the Garrison Dam, including areas on the right bank at river miles 1345; 1310; 1311; 1316.5; 1334.5; 1341; 1343.5; 1379.5; and on the left bank at river miles 1316.5; 1320.5; 1323; 1326.5; 1335.7; 1338.5; 1345.2; 1357.5; 1360; 1366.5; 1368; and 1374;

(4) The delta and hill areas of the Yazoo River Basin generally in accordance with the recommendations of Chief of Engineers in his report dated 23 September 1972;

(5) The delta of the Eel River, California;

(6) The lower Yellowstone River from Intake, Montana, to the mouth of such river.

d. Prior to construction of any projects under this section, non-Federal interests shall agree that they will provide without cost to the United States lands, easement, and rights-of-way necessary for construction and subsequent operation of the projects; hold and save the United States free from damages due to construction, operation, and maintenance of the projects; and operate and maintain the projects upon completion.

e. There is authorized to be appropriated not to exceed $50,000,000 to carry out this action.

f. The Secretary of the Army shall make an interim report to Congress on work undertaken pursuant to this section by September 30, 1978, and shall make a final report to the Congress no later than December 31, 1981.

APPENDIX B: LISTING OF COMMERCIAL CONCERNS THAT MARKET STREAMBANK PROTECTION PRODUCTS

1. A listing of commercial organizations that market streambank protection products is provided below.

Company	Address	Product(s)
Advance Construction Specialties Company	P. O. Box 17212 Memphis, Tenn. 38117	Filter cloths
Air Logistics Corporation	3600 East Foothill Blvd. Pasadena, Calif. 91109	Mo-Mat
ALCOA Marine Corporation	8235 Pen Randal Place Upper Marlboro, Md. 20870	Aluminum marine retaining walls (sheet piling)
American Excelsior Company	P. O. Box 249 Sheboygan, Wis. 53081	Curlex Blanket TM, Holdgro TM Fabric
ARMCO Steel Corporation	419 Chanin Bldg. 815 Connecticut Ave., NW Washington, D. C. 20006	Bulkheads
Bekaert Gabions	4930 Energy Way Reno, Nev. 89502	Gabions
Boiardi Products Corporation	211 E. 43rd St. New York, N. Y. 10017	Grasstone
Bomanite Corporation	81 Encina Ave., Palo Alto, Calif. 94301	Grasscrete
Bowie Industries	P. O. Box 931 Bowie, Tex. 76230	Hydro-Mulcher
Carthage Mills, Inc.	124 W. 66th St. Cincinnati, Ohio 45216	Plastic filter cloth
Celanese Fibers Marketing Company	1211 Avenue of the Americas New York, N. Y. 10036	Mirafi 140 fabric filter cloth
Conwed Corporation	760 29th Avenue, SE Minneapolis, Minn. 55414	Conwed erosion-control net and Hydro-Mulch
Construction Techniques, Inc.	11900 Shaker Blvd. Cleveland, Ohio 44120	Fabriform
DuPont	1007 Market St. Wilmington, Del. 19898	TYPAR filter cloth

(Continued)

Company	Address	Product(s)
Dowling Bag Company	P. O. Box 1768 Valdosta, Ga. 31601	Jute mesh
Edward E. Gillen, Company	218 W. Becher St. Milwaukee, Wis. 53207	Longard tubing and filter cloth
ERCO Systems, Inc.	P. O. Box 4133 New Orleans, La. 70178	Gobi (cellular) blocks
Erosion Control, Inc.	205 Datura St. West Palm Beach, Fla. 33401	Dura-Bags, fencing, artificial sea-weed filter cloth
Finn Equipment Company	P. O. Box 68 "Station O" Cincinnati, Ohio 45208	Equipment for broadcasting Hydro-Mulch
Firestone Coated Fabrics Co.	P. O. Box 887 Magnolia, Ark. 71753	Rubber-coated fabric tanks, Fabritank
Firewater Company	1 First St. Los Altos, Calif. 94022	Crust-500 (acetate emulsion)
GAF Corporation	140 W. 51st St. New York, N. Y. 10020	Corrugated canal bulkheading
Grass Growers, Inc.	P. O. Box 584 Plainfield, N. J. 07601	Terra Tack mulch binder
Grass Pavers, Ltd.	3807 Crooks Road Royal Oak, Mich. 48073	Monoslabs (cellular)
Grifflon Company, Inc.	P. O. Box 33248 Houston, Tex. 77033	Griff net
Gulf States Paper Corporation	P. O. Box 3199 Tuscaloosa, Ala. 35401	Erosion-control fabrics
Hold-That-River, Inc.	P. O. Box 45335 Houston, Tex. 77045	Timber fencing
Hudson Pulp and Paper Corporation	P. O. Box 919 Palatka, Fla. 32077	Paper riprap, bulkhead bags prefilled
Johns-Manville	Ken-Caryl-Ranch P. O. Box 5108 Denver, Colo.	Tile-Guard filter fabric
Kaiser Aluminum	300 Lakeside Dr. Oakland, Calif. 94643	Shore-All sheet piling

(Continued)

Company	Address	Product(s)
Kennross-Naue Canada, Ltd.	320 Alameda Drive Palm Springs, Fla. 33461	Filter cloth, cellular blocks, sand trap mats
Koch Brothers, Inc.	35 Osage Avenue Kansas City, Kans. 66105	Zenith filter
Louisiana Industries	P. O. Box 5396 Bossier City, La.	Monoslabs (cellular)
Ludlow Textiles	300 West Emory St. Dalton, Ga. 30720	Jute mats
Maccaferri Gabions, Inc.	RR#2, Box 43A Williamsport, Md. 21795	Gabions
Menardi-Southern	P. O. Box 12454 Houston, Tex. 21795	Monofilter (J. P. Stevens)
Monsanto Textiles Company	800 N. Lindbergh Blvd. St. Louis, Mo. 63166	BIDIM engineering fabric
Owens-Corning Fiberglas Corporation	Fiberglas Tower Toledo, Ohio 43659	Bituminous treated glass fibers
Ozite Corporation	1755 Butterfield Rd. Libertyville, Ill. 60048	HD-10 filter fabric
Phillips Petroleum Company	15D 2 Phillips Blvd. Bartlesville, Okla. 74004	Petroset rubberiz- ing emulsions
Reinco	P. O. Box 584 Plainfield, N. J. 07061	Equipment for broadcasting Hydro-Mulch; Terra Tack
Spidel Foundations Harbor and Marine Corporation	1055 North Shore Dr. Benton Harbor, Mich. 49022	Z-Wall piling
Superior Fiber Mulch	Suite 501 Executive Plaza II Hunt Valley, Md. 21031	Mulch
Soil Seal Corporation	600 S. Harvard Blvd. Los Angeles, Calif. 90005	Soil cement.

(Continued)

Company	Address	Product(s)
United States Textures Sales Corporation	4229 Jeffrey Drive Baton Rouge, La. 70816	Nicolon
VSL Corporation	236 N. Santa Cruz Ave. Los Gatos, Calif. 95030	VSL Hydro-Lining
Warren-Fondedile	675 Massachusetts Ave. Central Plaza Cambridge, Mass. 02139	Root piles

2. A limited number of research organizations direct part of their efforts toward the study of streambank protection. These organizations are listed below.

Organization	Address
Asphalt Institute	Asphalt Institute Bldg. College Park, Md. 20740
Bituminous Coal Research, Inc.	350 Hochbers Rd. Monroeville, Pa. 15146
Portland Cement Association	Old Orchard Rd. Skokie, Ill. 60076

APPENDIX C: GLOSSARY OF STREAMBANK PROTECTION TERMINOLOGY

Armor. Artificial surfacing placed on the banks of a stream to resist erosion or scour.

Articulated concrete mattress. Rigid concrete slabs usually hinged together with corrosion-resistant wire fasteners; primarily for lower bank protection.

Asphalt block. Precast or broken pieces of asphalt that can be hand-placed or dumped on a streambank or filter for protection against erosion.

Asphalt (bulk). Mass uncompacted asphalt usually dumped from a truck (upper bank protection) or a barge (lower bank protection) that is designed to stabilize the bank against erosion.

Bank protection. Placement of revetment or other armor to stabilize a streambank against erosion or use of a river training structure designed to deflect the hydraulic erosive forces away from a streambank.

Bituminous mattress. An impermeable rock-, mesh-, or metal-reinforced mattress of asphaltic or other bituminous material placed on a streambank to prevent erosion.

Bulkhead. A vertical or nearly vertical structure supporting a natural or artificial embankment.

Cellular block. Regularly cavitated concrete block placed directly on a streambank or filter to prevent erosion. The cavities permit the growth of either volunteer or planted vegetation.

Ceramic mattress. Ceramic slabs hinged together with corrosion-resistant fasteners placed on a streambank to prevent erosion.

Ceramic riprap. An armor of whole or broken ceramic blocks or slabs placed on a streambank or filter to prevent erosion.

Concrete block. Precast whole or broken concrete material placed on a streambank or filter to prevent erosion.

Crib. An open-frame structure filled with earth or stone ballast designed to absorb energy and to deflect hydraulic currents away from a streambank.

Cut bank. The concave wall of a meandering stream that is maintained as a steep or overhanging cliff by the impinging streamflow against its base.

Dike (sill, groin, spur, jetty). A river training aid constructed of earth, wood, or stone, designed to deflect erosive currents away from a bank and to control movement of bed material.

Erosion-control matting. Fibrous matting (e.g. jute, paper, fiberglass, etc.) placed or sprayed on a streambank for the purpose of preventing erosion or providing temporary stabilization until vegetation is established.

Fascine. A bundle of brush, sticks, or timber used to make a foundation mat or to make a revetment to protect a streambank against erosion.

Fence. A river training structure normally consisting of mesh attached to a series of posts often in double rows; the interstitial space between the rows may be filled with rock, brush, or other locally available materials.

Filter. Layer of sand, evenly graded rock, or cloth, placed between the bank armor and soil for one or more of three purposes: to prevent the soil from coming through the armor by extrusion or erosion, to prevent the armor from sinking into the soil, and to permit natural seepage from the streambank to occur and thus prevent buildup of excessive hydrostatic pressure.

Freeze probe. A steel cylindrical bar used as a soil stabilization technique in polar climates to maintain bank stability and retard erosion by freezing the soil during warm months.

Gabion. A wooden, wire mesh, or cloth basket or cage filled with earth, stone, or other locally available material placed as a component of a bank protection structure.

Grout. A fluid mixture of cement and water or of cement, sand, and water used to fill joints and voids.

Jack (Jackstraw, Kellner jack). A component of a river training structure consisting of wire or cable strung on three mutually perpendicular metal, wooden, or concrete struts.

Log and cable. Trees or timber anchored to a streambank by a series of cables to serve as protection against erosion.

Lower bank. That portion of a streambank having an elevation less than the mean water level of the stream.

Mattress. A broad flat cage or network of concrete, wood, stone, or other locally available materials used to protect a streambank against erosion.

Organic mixtures and mulches. Any of a number of organic agents (e.g. petrochemicals or vegetative matter) used to stabilize a streambank against erosion by affording permanent protection or temporary protection and nutrients for the establishment of vegetation. These agents, which may be in the form of liquids, emulsions, or slurries, are normally applied by means of mechanical broadcasters.

Pavement. Streambank surface covering, usually impermeable, designed to serve as armor against erosion. Common pavements used on streambanks are concrete and compacted asphalt.

Pile. An elongated member, usually made of timber, concrete, or steel, that serves as a structural component of a river training structure.

Point bar. The convex side of a loop of a meandering stream where active deposition of bed load and suspended sediment load occurs.

Revetment. Armor of erosion-resistant material designed to protect a streambank.

River training structure. Any configuration constructed in a stream or placed on, adjacent to, or in the vicinity of a streambank, which is intended to deflect currents, induce sediment deposition, induce scour, or in some other way alter the velocity regimen of the stream.

Rock-and-wire mattress. A flat or cylindrical wire cage filled with stones or other suitable material placed on a streambank as armor against erosion.

Rubble. Rough, irregular fragments of random size placed on a streambank to retard erosion. The fragments may consist of broken concrete slabs, masonry, or other suitable refuse.

Sack revetment. A revetment consisting of sacks (e.g. burlap, paper, or nylon) filled with concrete, sand, stones, or other available material placed on a streambank to serve as protection against erosion.

Soil cement. A mixture of soil and portland cement at a prescribed moisture content that is compacted to provide stability for a soil surface and to prevent its erosion.

Soil fusion. A process to stabilize a streambank by heating the soil.

Stone riprap. Natural cobbles, boulders, or broken stones dumped or placed on a streambank or filter as armor against erosion.

Synthetic mattress, matting, casing, and tubing. A grout- or sand-filled, manufactured, semiflexible casing placed on a streambank to prevent erosion.

Tetrahedron. Component to river training works made of six steel or concrete struts fabricated in the shape of a pyramid.

Tetrapod. Bank protection component of precast concrete consisting of four legs joined at a central block, each leg making an angle of 109.5 deg with the other three.

Timber-and-brush mattress. A mattress made of brush, poles, logs, or lumber interwoven or otherwise lashed together. The resulting configuration is then placed on the bank of a stream and weighted with natural or artificial stone ballast.

Toe. That portion of a stream cross section where the lower bank terminates and the channel bottom or the opposite lower bank begins.

Trench-fill revetment. Stone, concrete, or ceramic material placed in a trench dug behind and parallel to an eroding streambank. When the erosive action of the stream reaches the trench, the material placed in the trench retards further erosion.

Upper bank. That portion of a streambank having an elevation greater than the mean water level of the stream.

Vegetation. Woody or nonwoody plants used to stabilize a streambank and retard erosion.

APPENDIX D: LITERATURE SURVEY OF STREAMBANK PROTECTION

1. An index is provided below as an aid for locating references on individual protection methods.

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Keown, Malcolm Price
Literature survey and preliminary evaluation of streambank protection methods, by M. P. Keown, N. R. Oswalt, E. B. Perry [and] E. A. Dardeau, Jr. Vicksburg, U. S. Army Engineer Waterways Experiment Station, 1977.
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